Measurement of primary coolant flow rate from a pressure difference

Romain CAMY with the help of *Code_Saturne* team and Open CASCADE support - May 2019

EDF/DIPNN/TECHNICAL DIRECTION

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Principle of primary flow rate measurement

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Balance of enthalpy

In a Pressurized Water Reactor (PWR), mass flow rate ($\dot{m}_i$) in each loop is derived from the **thermal power at the steam generator** ($SG\ i$), the **temperatures in hot and cold legs** ($T_{HL,i}$ and $T_{CL,i}$) and the **electric power absorbed by the Reactor Coolant Pumps** ($\dot{W}_{RCP}$).

$$\dot{W}_{SG,i} = \dot{m}_i \left(h(T_{HL,i}) - h(T_{CL,i}) \right) + \frac{\dot{W}_{PPump}}{4}$$

Only once at the beginning of a fuel cycle.

Possible impact

From [Lish 2017]: *Inaccurate flow monitoring can result in power downrating and unnecessary downtime.*

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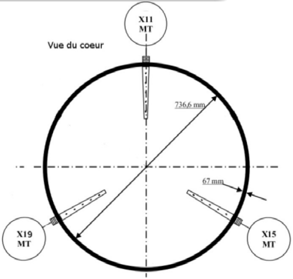

Temperature measurement and *Code_Saturne* results [Bellet 2017]

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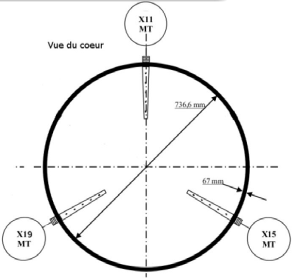

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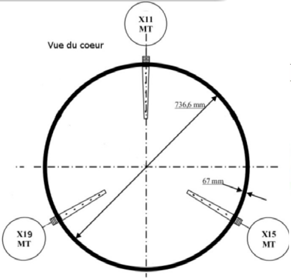

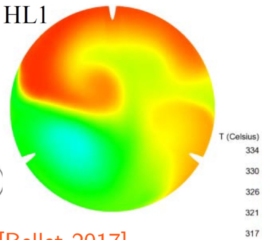

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Principle of primary flow rate measurement

Pressure difference

Use a **pressure difference** between both sides of the first elbow after steam generator ΔP_{elbow} to estimate the volumetric flow rate ($\dot{V}_i$) with

$$\dot{V}_i = K D^{3/2} Rc^{1/2} \sqrt{\frac{\Delta P_{elbow}}{\rho}}$$

- K a constant depending on the locations of the pressure probes,
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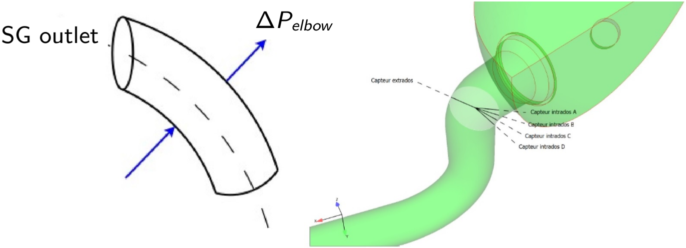

Schematic view ΔP_{elbow} measure [Mercier 2015]

Presentation of the integral effect test

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EVEREST "SG water box - crossover leg"

- **1:4 scaled-down model** of cold side SG water box loop 2 of Chooz B1 French PWR.
- Tests in **2000 and 2010**.
- Experimental uncertainty quantification.
- In crossover leg $Re \in [8.3\,10^5, 2.6\,10^6]$
  $\rightarrow y^+ = 1 \Leftrightarrow \Delta y < 13\mu m$
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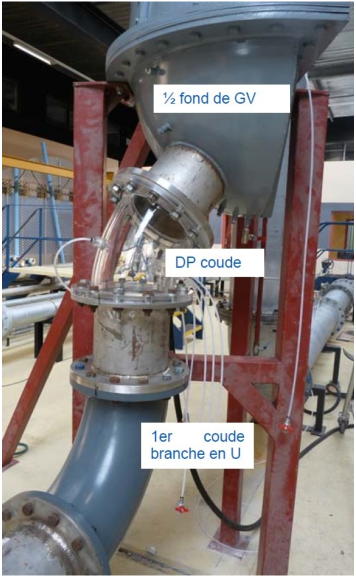

Experimental setup in Chatou (France)

Zoom on the mesh generation

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What makes a mesh good ?

- **adapted to the physics** (boundary layer, alignement with streamlines, ...)
- **hexaedra** > other elements
- **conformal mesh**
- **good quality criteria**
- **good looking**

How to ?

No known algorithm able to mesh an arbitrary volume with conformal hexaedra (with the constraint to respect the initial volume) → **"blocking"**.

2 possible strategies:

- use assistance from **predefined patterns**,
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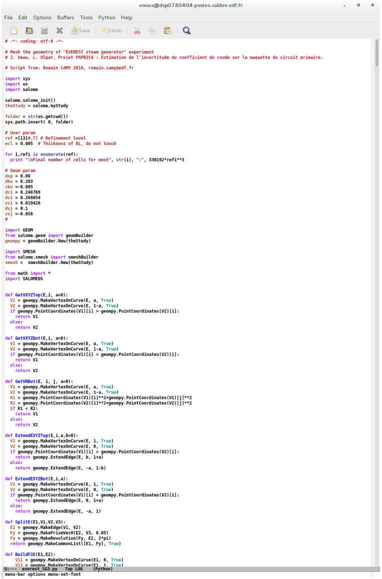
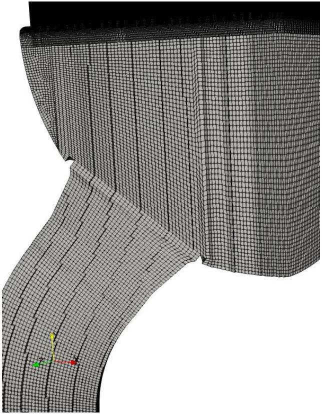


CAD with GEOM (1322 lines)

Zoom on the mesh generation



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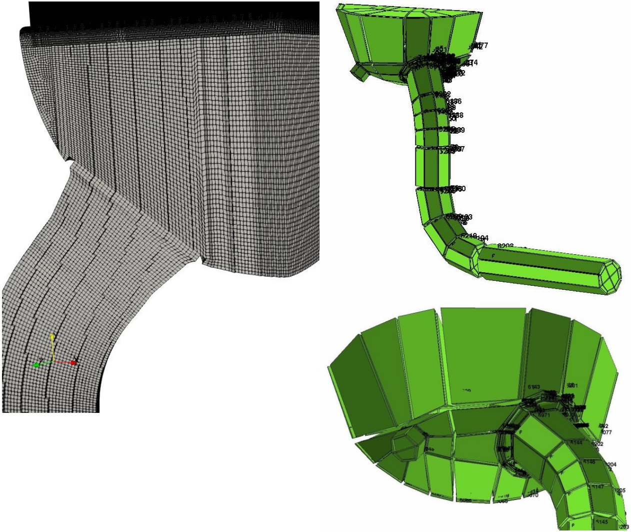

Recent realisations from 2 service providers and present work

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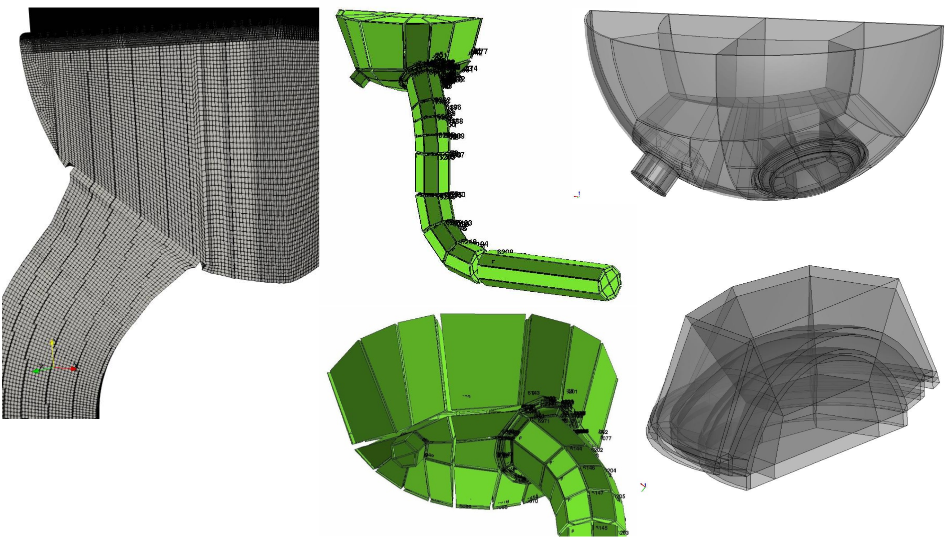

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Used mesh technique in present work

Blocking made **in 2 steps** with **parallel joining** in *Code_Saturne* (conformal).

- $\rightarrow$ easier to setup and debug,
- $\rightarrow$ overcome the limitation of $\approx$ 200 M cells for a mesh in SMESH (and faster).

Large range of refinement levels: from 330 K (ref. 1) to 2.64 B cells (ref. 20)
0 bad cell but $>$ 0.05% *"faces have a too large reconstruction distance"*

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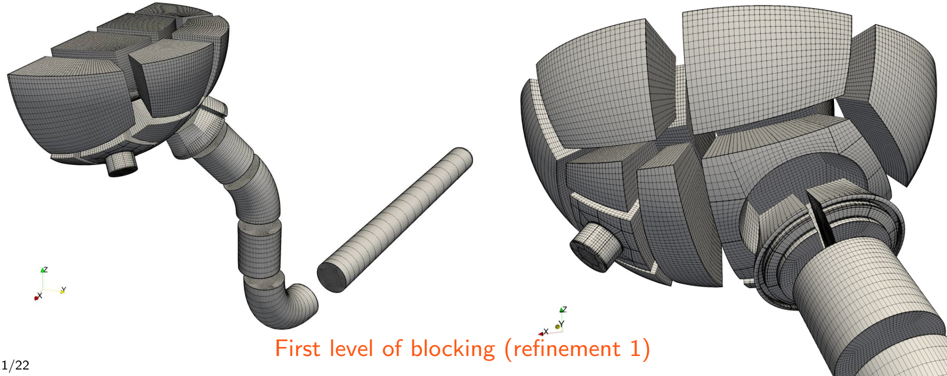

First level of blocking (refinement 1)

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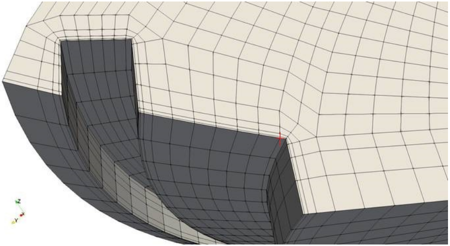

Ref. 1 (330 K cells)

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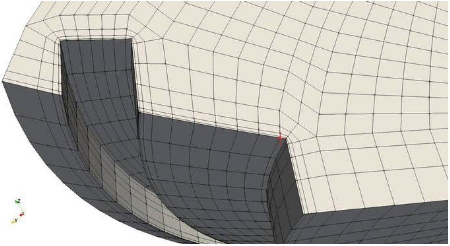

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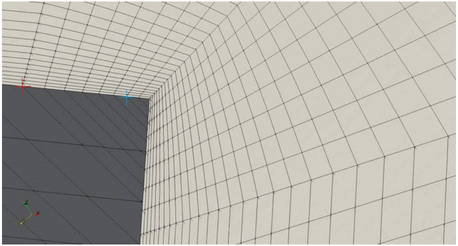

Ref. 8 (169 M cells)

Ref. 8: $y^+ \approx 2$, $z^+ \approx 70$, $x^+ \approx 186$ and $\overline{\nu_t}/\nu \approx 0.3$ with $\nu_{t,max}/\nu \approx 6$.

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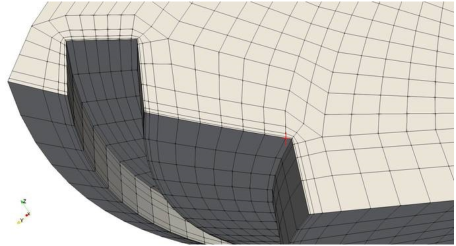

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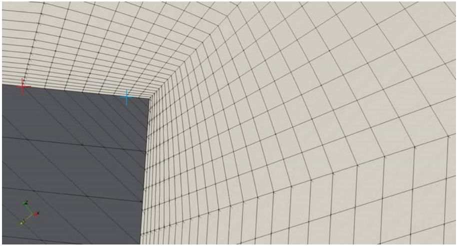

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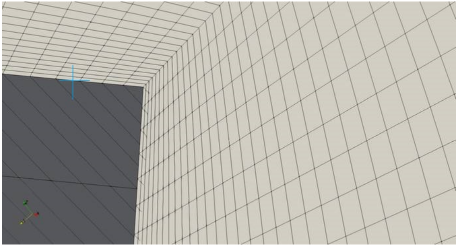

Ref. 13 (725 M cells)

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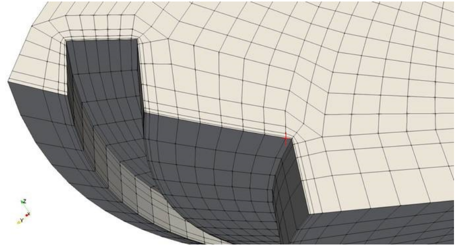

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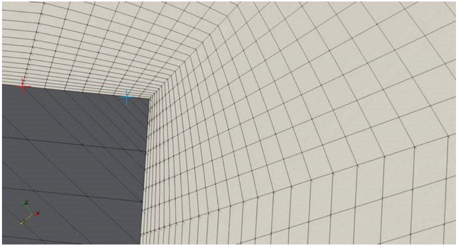

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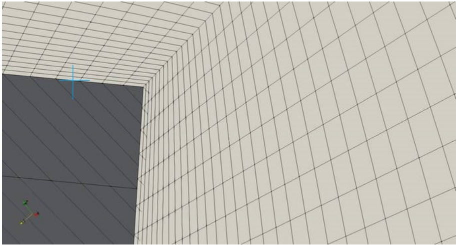

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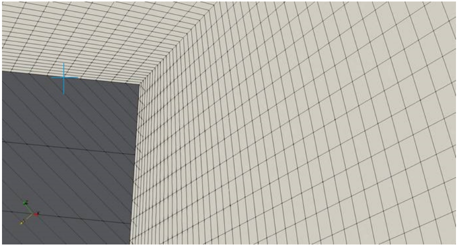

Ref. 20 (2.64 B cells)

Details on calculations setup

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Models and numerical parameters

- **Unsteady** with constant time step,
  - in RANS: $CFL_{max} < 20$ and $CFL_{moy} \approx 0.05$,
  - in LES: $CFL_{max} < 10$ and $CFL_{moy} \approx 0.05$.
- In LES, **Smagorinsky model** and 2% upwind for momentum.
- In RANS, **wall resolved models**: $k - \omega$ & EB-RSM and pure central scheme.
- Inlet jets simulated with **non uniform inlet velocities**.

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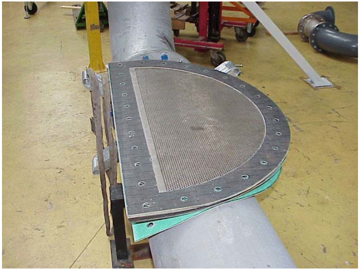
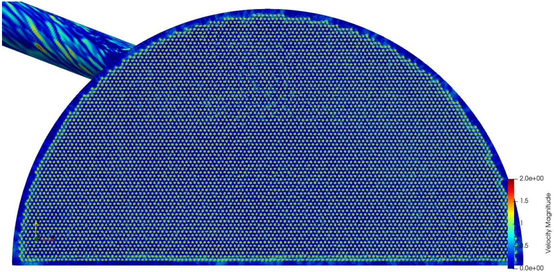


Inlet slab



Inlet velocities (ref. 8 mesh)

Calculations results compared to experiment

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Different models tested on different meshes

The general shape of the streamlines are **consistent with each other**. More specifically:

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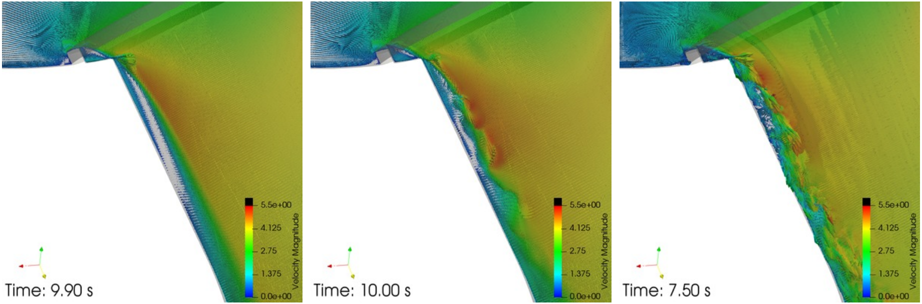

From left to right: ref. 5 $k - \omega$ & EB-RSM, ref. 8 LES

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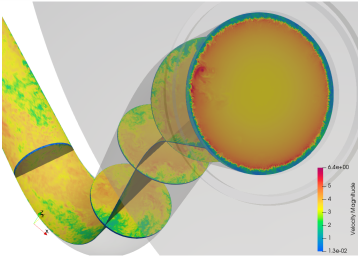

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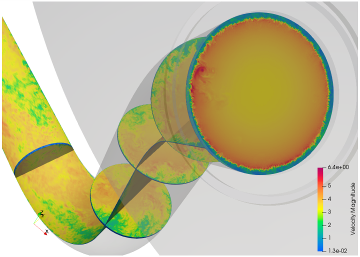

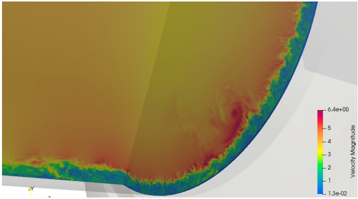

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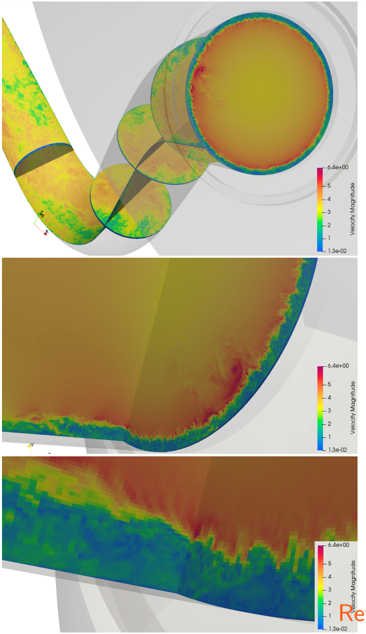

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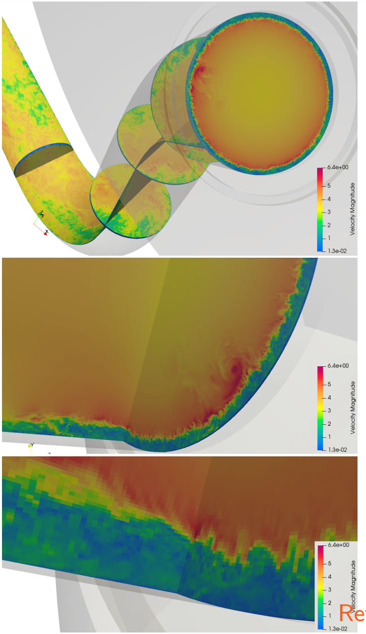

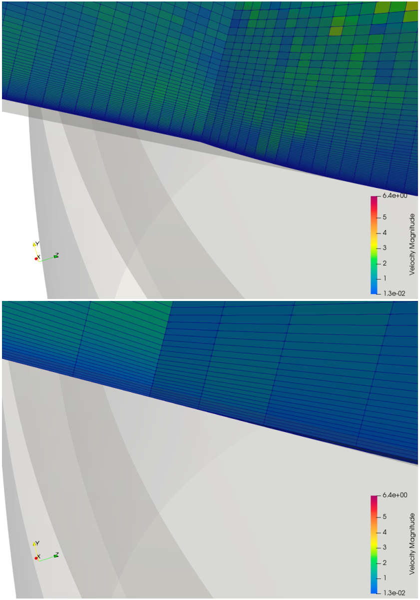

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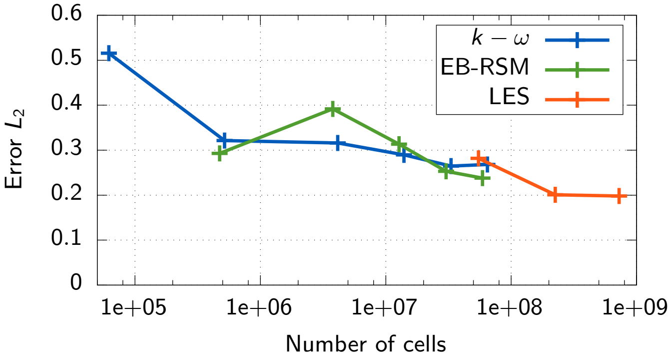

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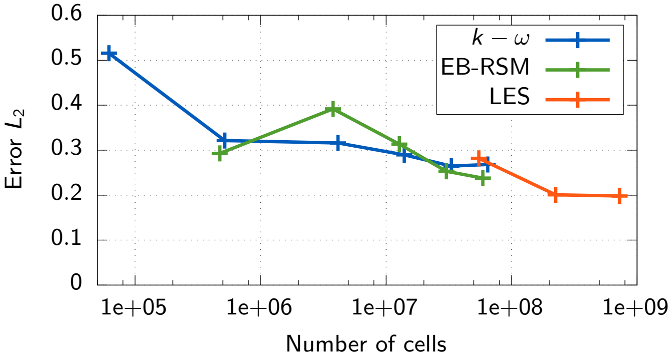

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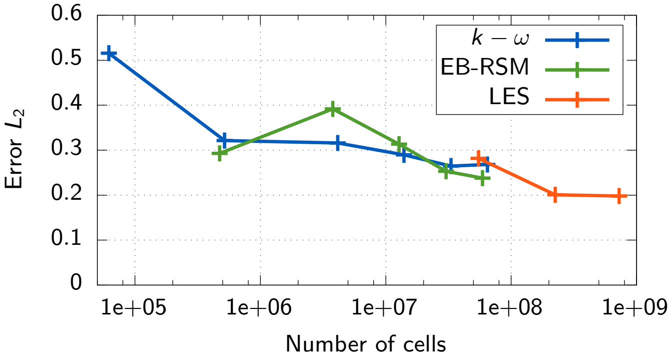

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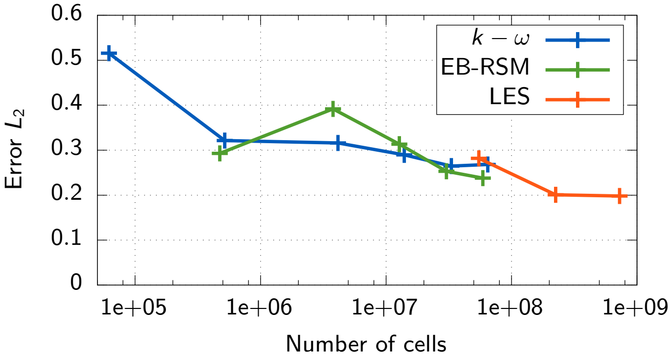

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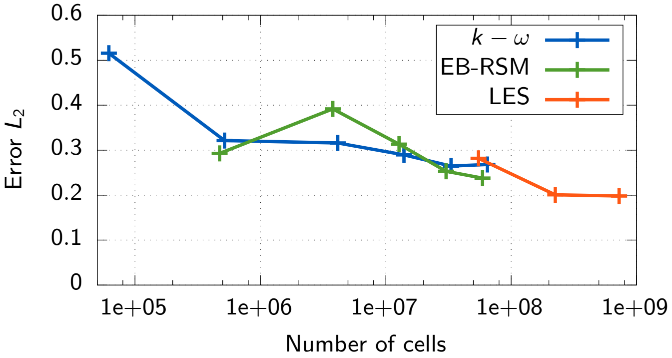

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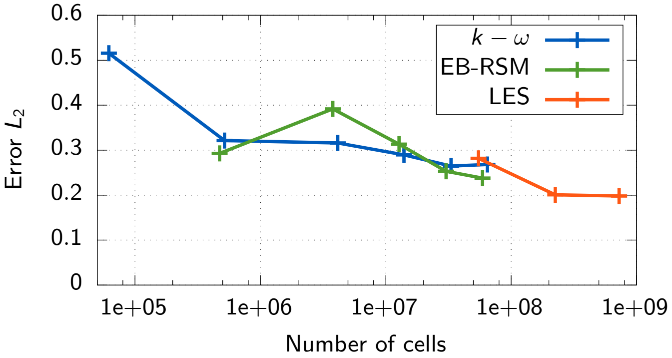

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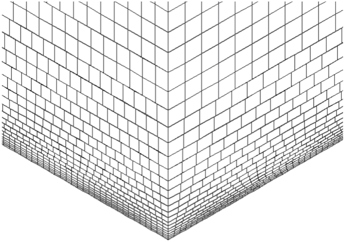

Taylor scale based mesh [Addad 2008]

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Thank you

Any questions ?

Turbulent luminance in impassioned van Gogh paintings. J. L. Aragón et al.