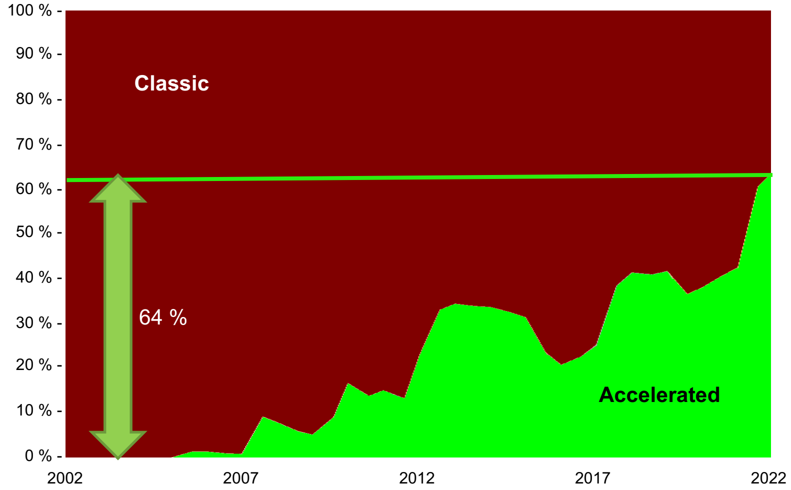
CExA project

Towards a Middleware to operate GPUs in Exascale context (Mission and Use Cases)

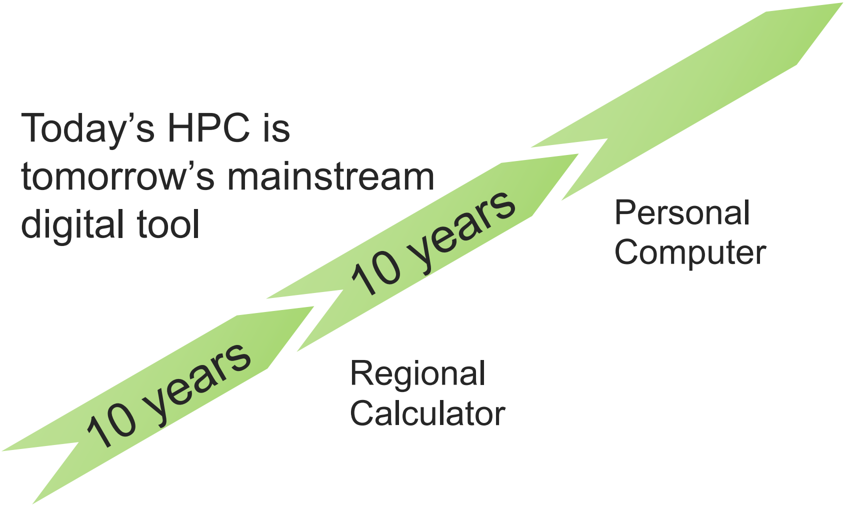
ADAC – 27 sept. 2023 – Fabien Baligand, CEA and Edouard Audit, CEA

Context

- Intensive computing : a transversal tool for **sovereignty** and **competitivity**
  - Numeric twins, climte modelling, nuclear dissuasion, physics at extreme scales, multi scale design of materials, personnalized medecine, privacy, etc.
  - Infused in society, transversal to all directions of CEA
- **Exascale** era is starting (1st machine this year)
  - Accelerated architecture (GPU)
  - First supercomputers coming to Europe in 2024-2025
    - An Exascale computer in France at CEA/TGCC
  - Need to revelop applications to benefit from it
- GPU Middleware : **catalysts**
  - Performances portability
  - In the US : driven by the *Exascale Computing Project* (ECP) ⇒ Kokkos
    - OSS strategy to ease transfert to industries
  - In Europe and in France : research, but no technology yet
- **Yearning** for sovereign solution
  - Control roadmap, adapt to our specific needs (HW and SW)



Computing power of the top 500 supercomputers in the world



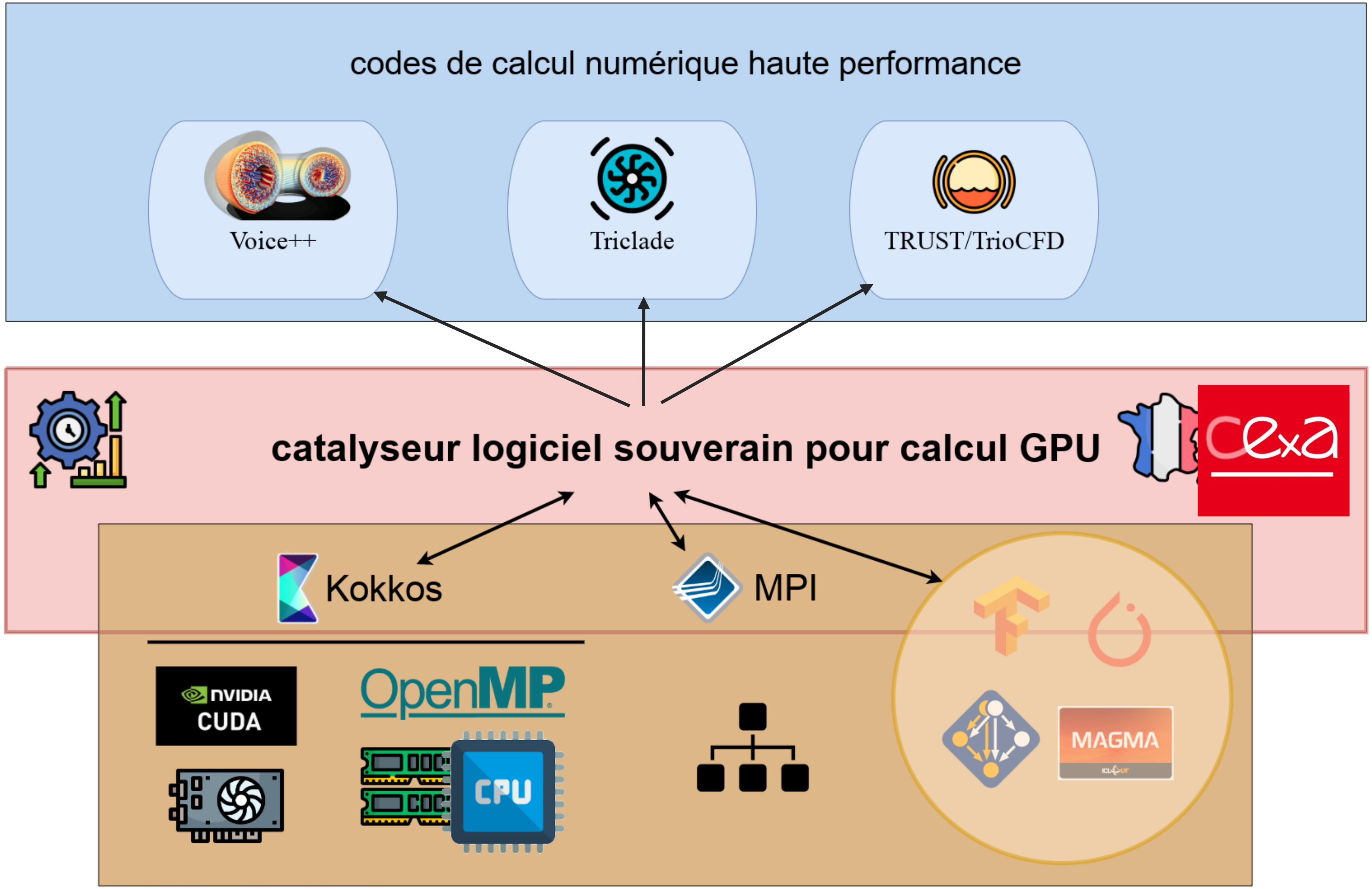
Today's HPC is tomorrow's mainstream digital tool

Personal Computer

Regional Calculator

Bleeding edge HPC

The project



codes de calcul numérique haute performance

Voice++

Triclade

TRUST/TrioCFD

catalyseur logiciel souverain pour calcul GPU

Communicate and Train to CExA inside CEA and outside

Adapt Use Case integrating CExA

Build a sovereign GPU computing software catalyst : CExA

CExA briefly

“adopt and adapt” Strategy based on Kokkos

- Kokkos : a **powerful platform**
  - Mature, free and open source
  - An architecture for performance portability
    - Ready for future machines
  - An integration step towards standard C++
    - Springboard towards standard C++
    - A preview of parallel C++

- Some **required adaptations**
  - For European hardware
    - No hardware sovereignty without software sovereignty
  - For CEA and European applications
    - Take specificities into account

Adequation to « distributed memory » applications

- **Performance portability MPI+Kokkos CPU & GPU**
- **Efficient memory transfer**
- **Supports for GPU virtualization**

Interface with 3rd party data processing tools

- **Interface with Pytorch, Tensorflow**
- **Linear algebra batching**

Heterogeneous architecture support

- **Multi-architectures code support**
- **Multi space execution support**
- **EPI processors support**

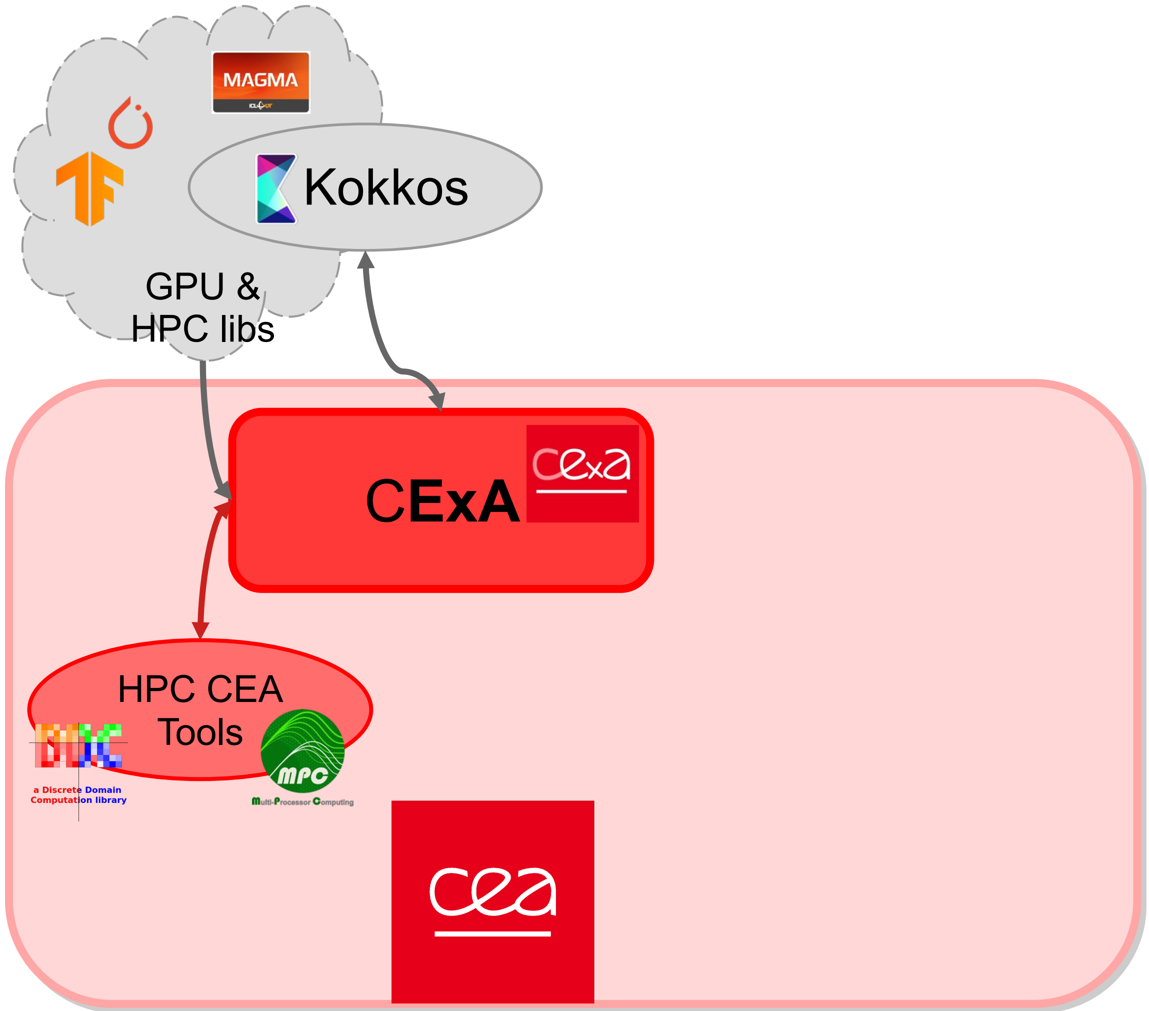
Ease of deployment on our computers

- **Multi-device deployment management**
- **Continuous Integration and installation on our computers**

Hardware specificities

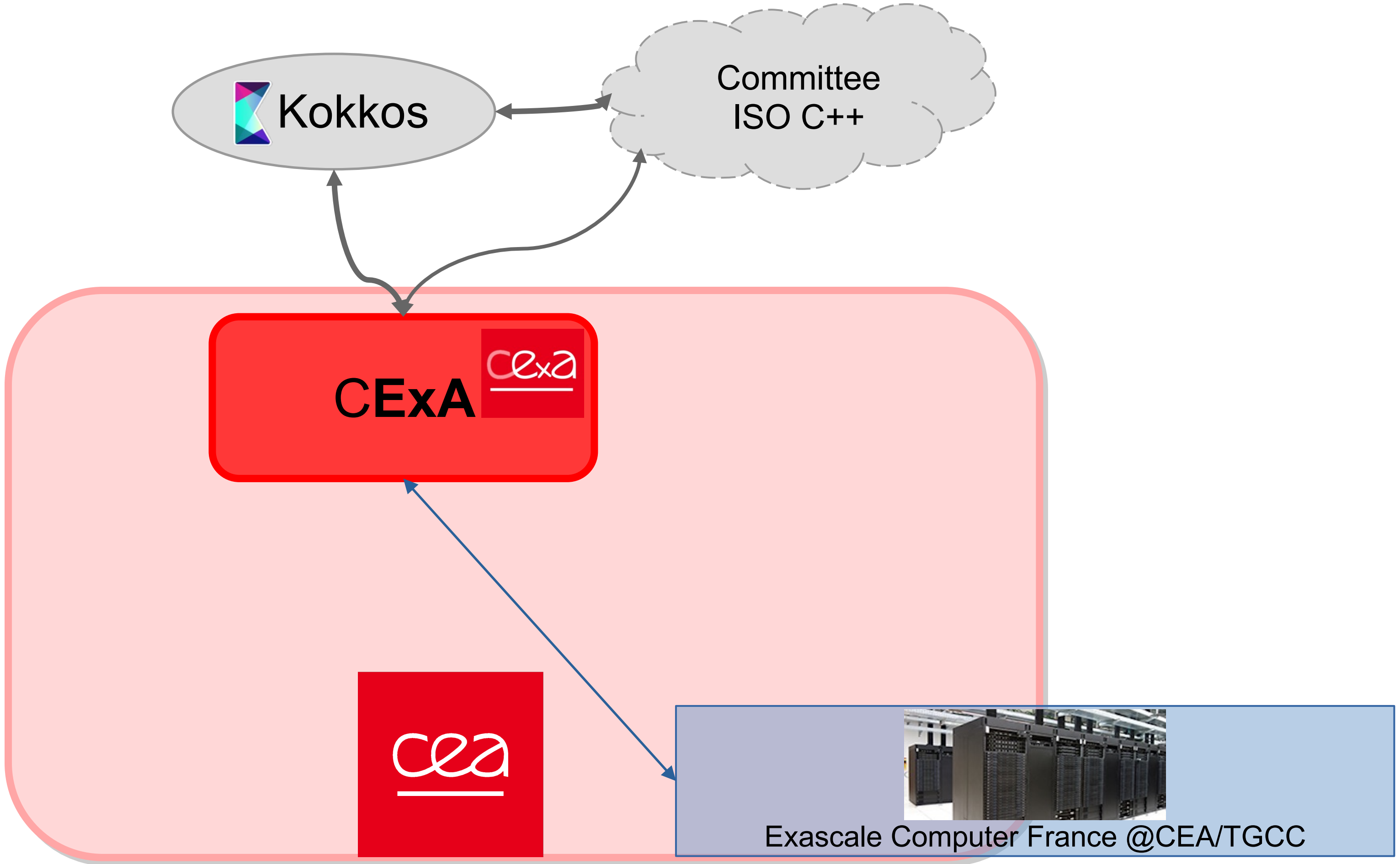
Software specificities

CExA Ecosystem: Upstream



- GPU & HPC Libraries
  - Tensorflow, Pytorch, MAGMA, etc.
  - Interface enabler with Open source software
- Kokkos development team
  - Strong connections
  - Here today (and at CEA last week)
- HPC CEA Libraries
  - MPC, DDC, Arcane, etc.
  - Integration and communications

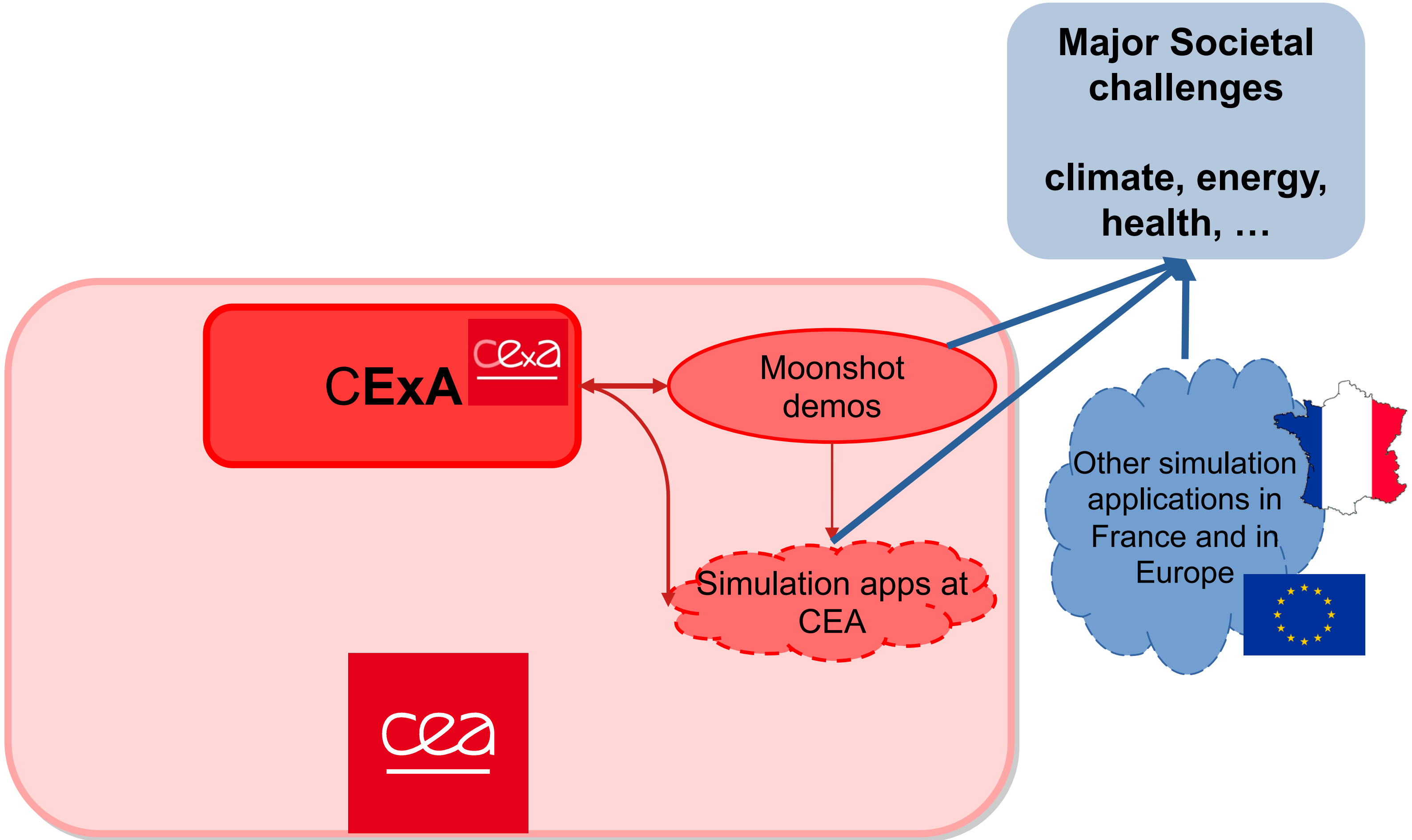
CExA Ecosystem: Partners



- Kokkos & ISO C++ committee
  - Standardization
    - Through Kokkos
  - Normalization et perennisation of CEA approaches

- Jules Vernes Project (Exa France)
  - Strong connections with GENCI, TGCC and NumPEx
  - AAP end of 2023
    - CExA requirements
  - Answer in 2024
    - Choice of architecture
  - Ship end of 2025
    - CExA production ready

CExA Ecosystem: Downstream



Major Societal challenges

climate, energy, health, …

CExA

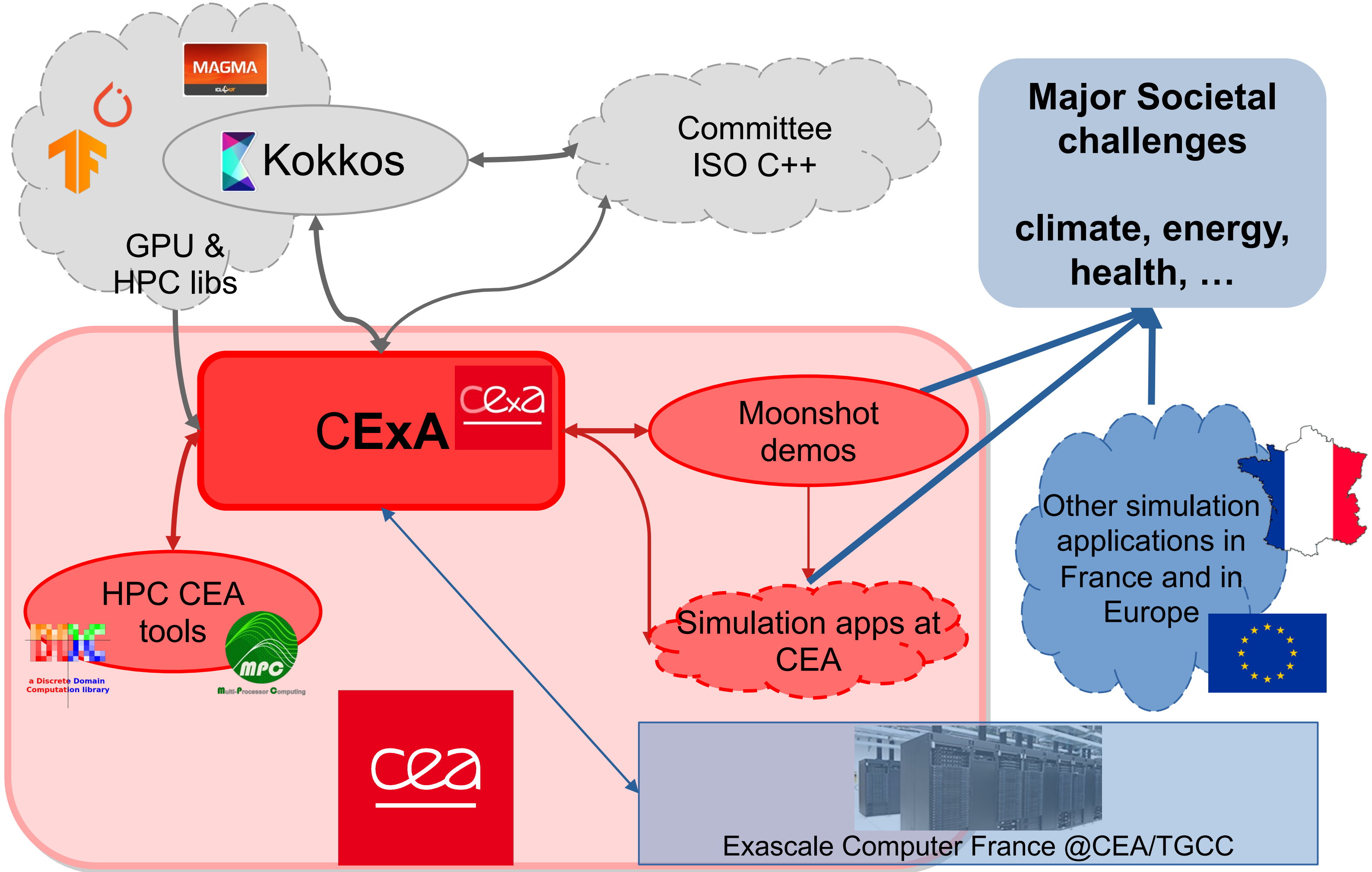
Moonshot demos

Simulation apps at CEA

Other simulation applications in France and in Europe

- Two layer downstream
  - Acceleration layer ⇒ applications
  - Second layer ⇒ societal challenges
- Integrated use cases
  - Co-design teams
  - Team training
  - Outcomes in critical domains
- CEA Applications
  - Training, hackathons, experience
  - Dynamic, opiniated
  - Community creation
  - CEA contributions ⇒ societal challenges
- FR and EU communities
  - CEA Visibility and role

CExA Ecosystem: Follow up



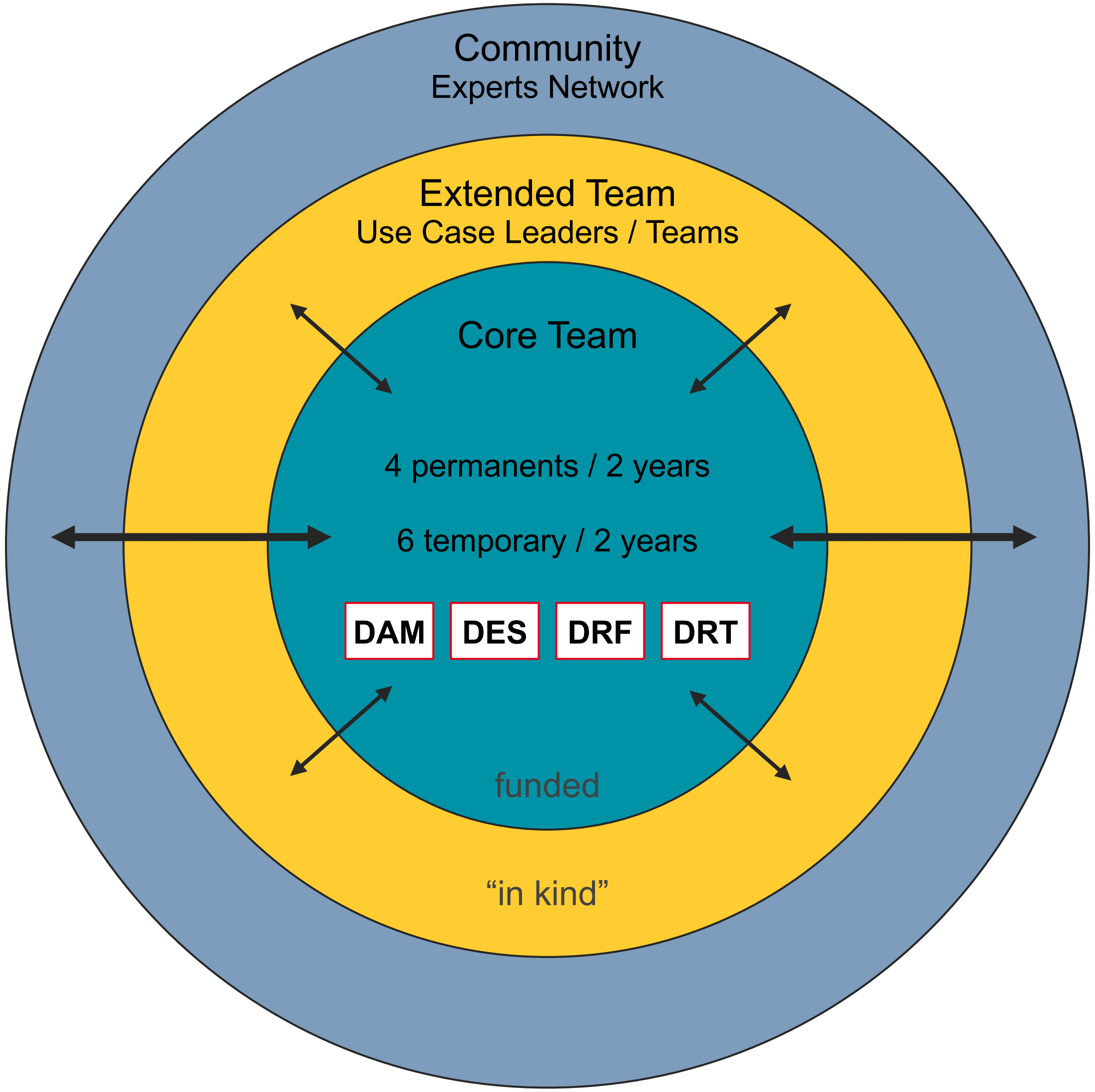
MAGMA
Kokkos
GPU & HPC libs
Committee ISO C++
Major Societal challenges
climate, energy, health, …
CExA
Moonshot demos
HPC CEA tools
a Discrete Domain Computation library
MPC
Multi-Processor Computing
Simulation apps at CEA
Other simulation applications in France and in Europe
Exascale Computer France @CEA/TGCC

- Preparation of tooling for numerical computing on GPU
  - After graphism (1990's)
  - After neural networks (end of 2000)

- At the heart of the stack
  - Expertise on tooling
  - Bleeding edge
  - Suiting roadmap

- A unique competitive edge for years to come

Team Structure

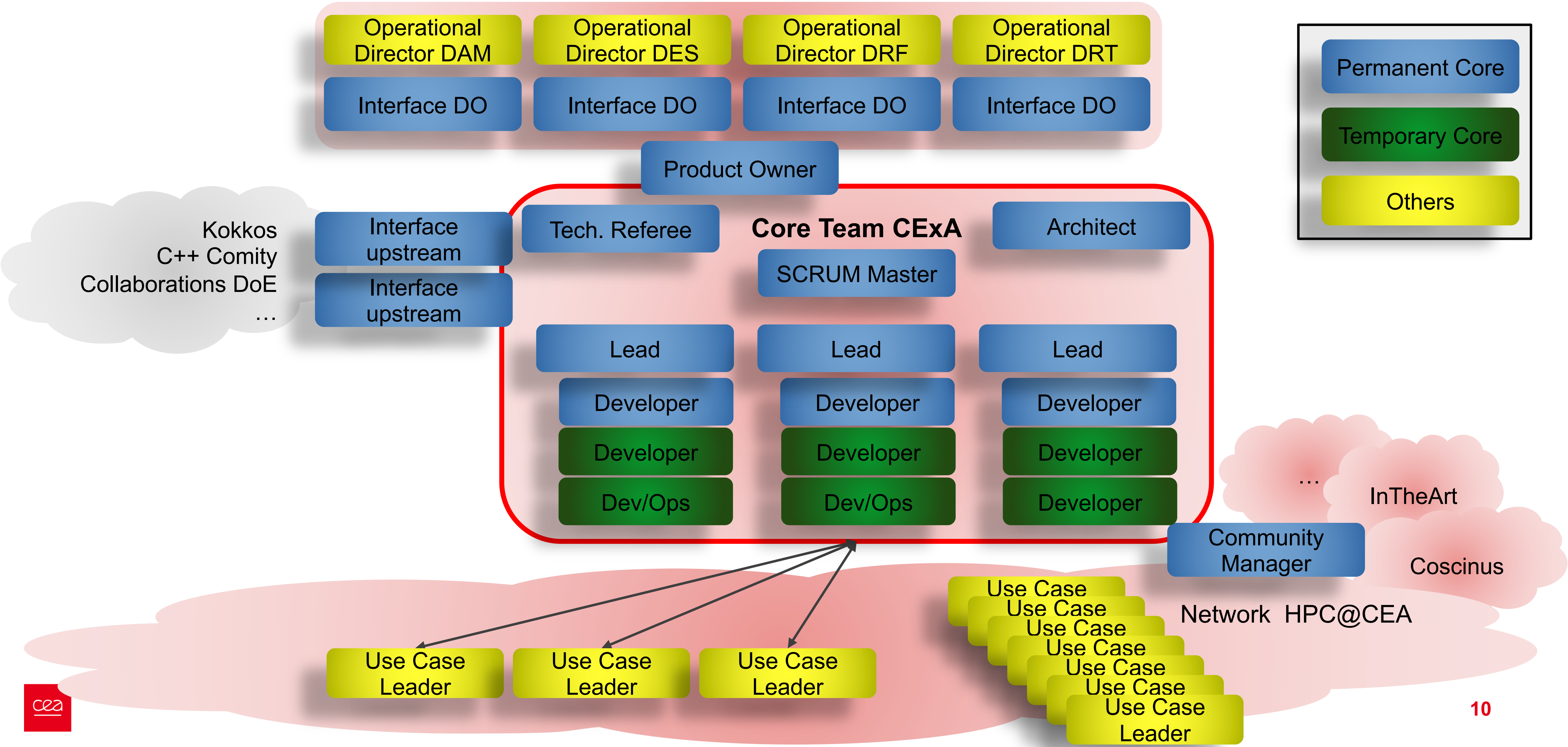


- Core Team
  - Management, Implementation and Dissemination
  - 4 permanent funded for 2 years
  - 6 temporary funded for 2 years
  - team organical growth

- Extended Team
  - Include use case leaders
  - 1 per DO (“in kind”)
  - ~6 months

- Community
  - Expert network federation
  - CExA co-design:
    - Backlog creation
    - CExA integration into applications
  - Dissemination targets
  - Work durability

Agile execution



Operational Director DAM

Operational Director DES

Operational Director DRF

Operational Director DRT

Interface DO

Interface DO

Interface DO

Interface DO

Product Owner

Kokkos
C++ Comity
Collaborations DoE
…

Interface upstream

Interface upstream

Tech. Referee

Core Team CExA

Architect

SCRUM Master

Lead	Lead	Lead
Developer	Developer	Developer
Developer	Developer	Developer
Dev/Ops	Dev/Ops	Developer

…

InTheArt

Community Manager

Coscinus

Network HPC@CEA

Use Case Leader

Use Case Leader

Use Case Leader

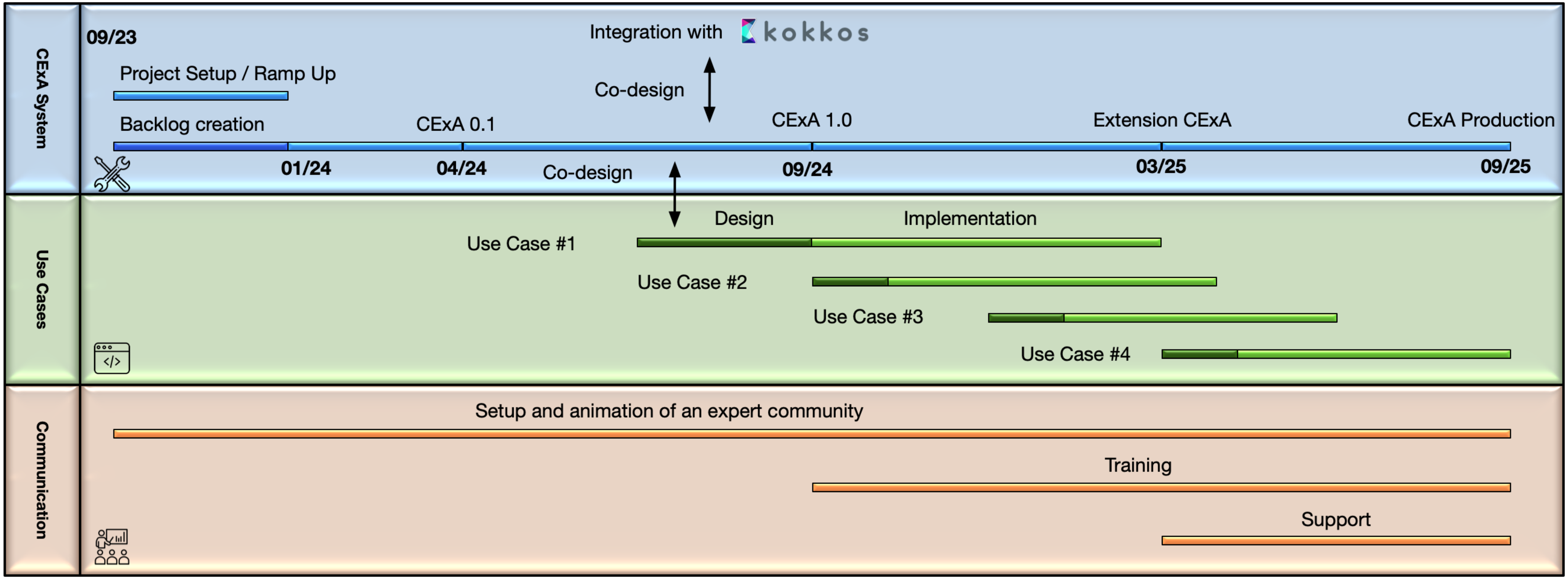
Use Case
Use Case
Use Case
Use Case
Use Case
Use Case
Use Case Leader

Permanent Core

Temporary Core

Others

Planning

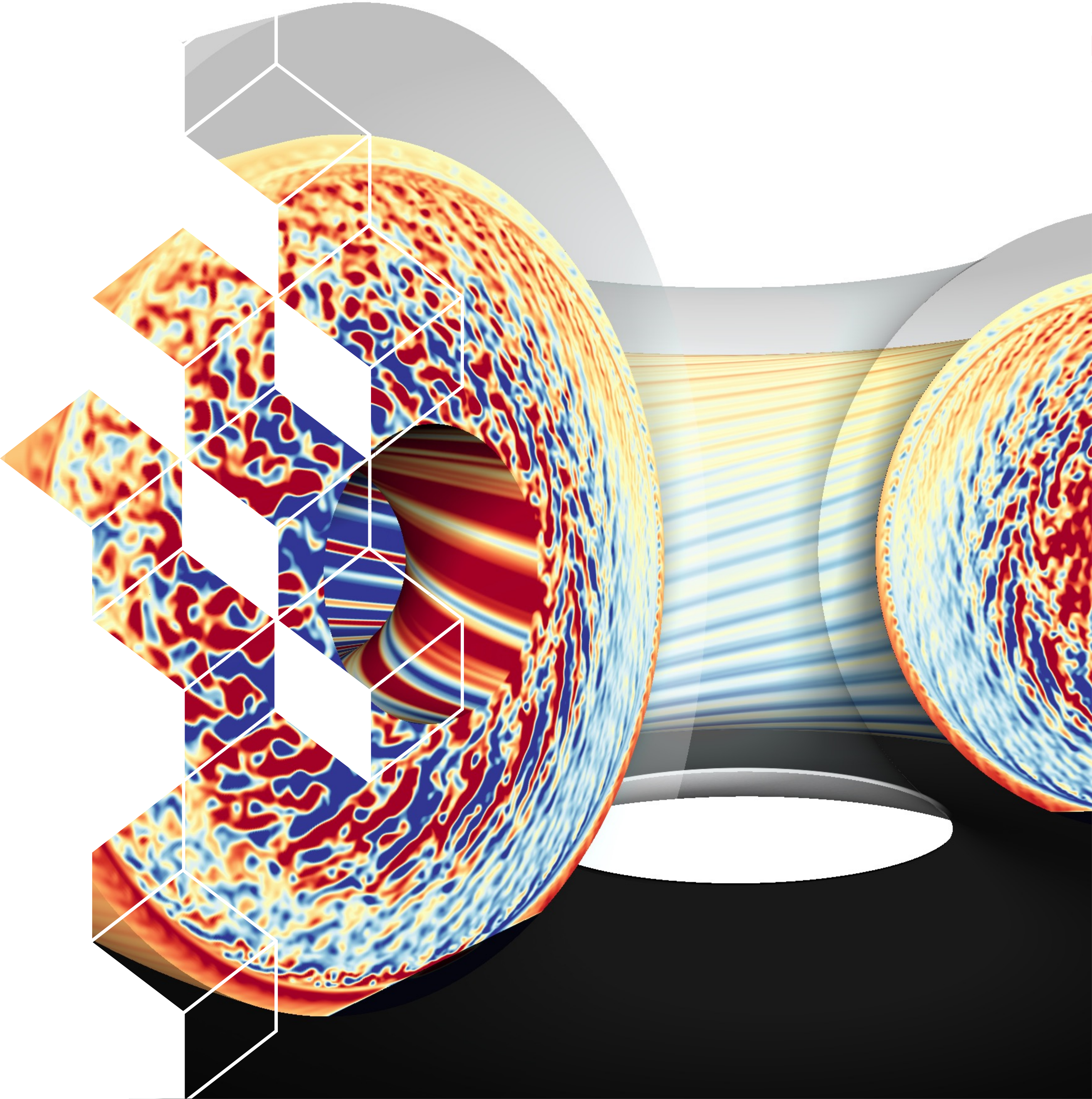

CExA System
09/23
Integration with kokkos
Co-design
Project Setup / Ramp Up
Backlog creation
CExA 0.1
CExA 1.0
Extension CExA
CExA Production
01/24
04/24
Co-design
09/24
03/25
09/25
Use Cases
Design
Implementation
Use Case #1
Use Case #2
Use Case #3
Use Case #4
Communication
Setup and animation of an expert community
Training
Support

Initial Backlog Epics

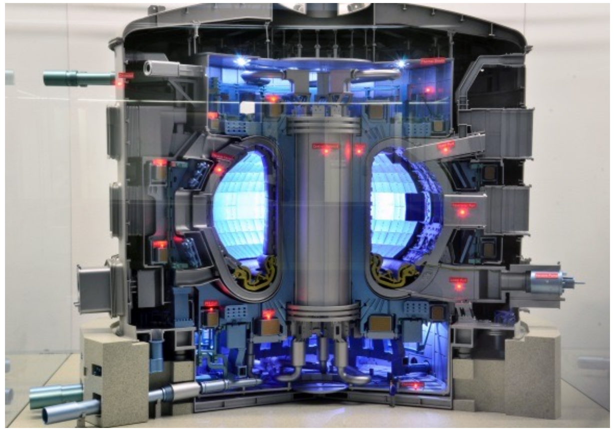
- Introduce physical variables management to write more robust simulation applications
- Facilitate port legacy of applications to accelerators hardware (GPU)
- Offer support to advanced and state of the art 3rd party functions/libraries (each vendor has its own library, plug to the right library via Kokkos level interfaces/adapters)
- Make full use of current and future European Exascale architectures
- Extend programming model to cover more usage scenarios
- Improve scientific applications Development by introducing Continuous Integration Facility
- Use Cases improvements (KPIs)
- Support CEA Technical Community

GyselaX++

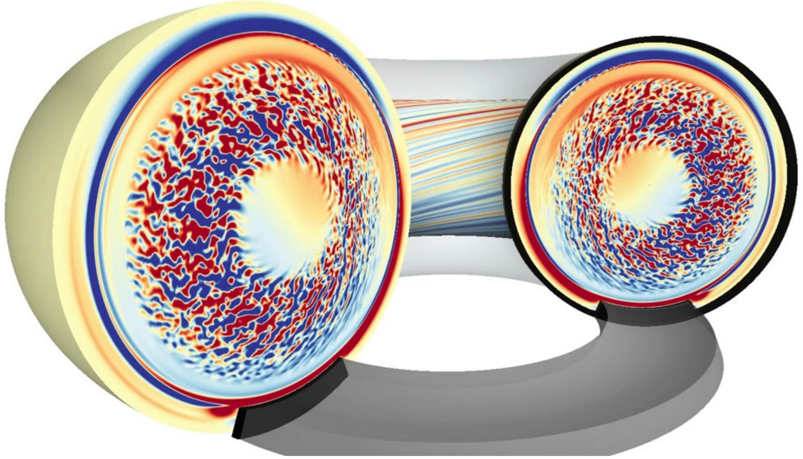
Exascale Challenges for tokamak plasma turbulence simulations



First principle simulations required for ITER
→ Gyrokinetic plasma turbulence simulations



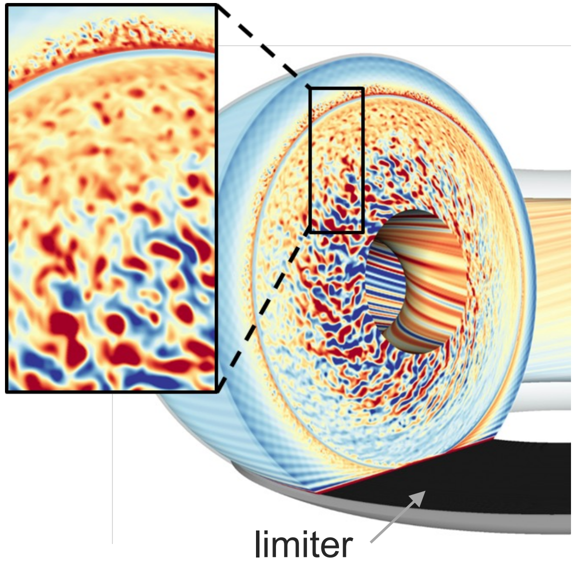
ITER project



GYSELA simulation

- To optimize performance and minimize risks, each ITER scenario will have to be numerically validated.
- A complete chain of numerical tools will be required, ranging from scale models, which can be used in real time, to first-principles simulations, which are more costly but more reliable.
- Turbulent transport mainly governs confinement in Tokamaks
- Tokamak plasmas weakly collisional → Kinetic approach mandatory
  - Fusion plasma turbulence is low frequency → fast gyro-motion is averaged out
  - Gyrokinetic approach: phase space reduction from 6D to 5D

GYSELA: a highly parallelised code running at petascale



- Gyrokinetic codes require state-of-the-art HPC techniques and must run efficiently on several thousand processors
  - Non-linear 5D simulations (3D in space + 2D in velocity)

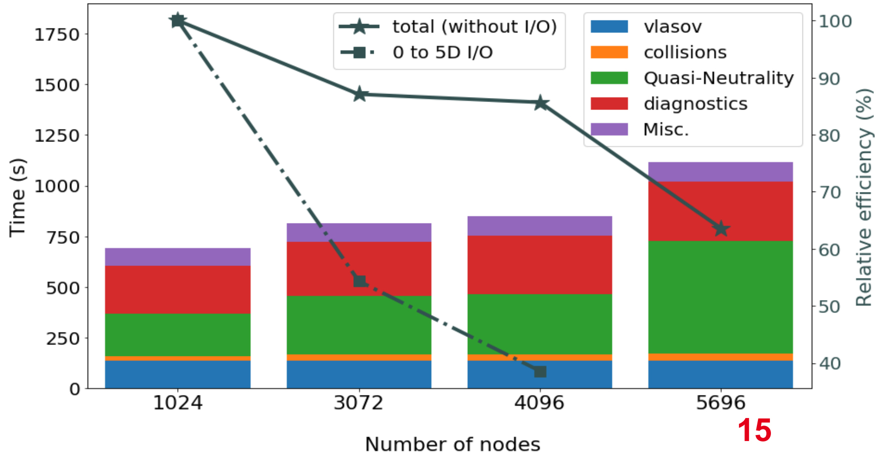
    + multi-scale problem in space and time

- Even more resources required when modelling both core & edge plasmas like GYSELA

- GYSELA = Fortran 90 code with hybrid MPI/OpenMP parallelisation optimized up to 730,000 cores
  - **Relative efficiency of 85% on more than 500k cores** and 63% on 730k cores on CEA-HF (AMD EPYC 7763)

- **Intensive use of petascale resources**: ~ 150 millions of hours / year
  - (GENCI + PRACE + HPC Fusion resources)

Weak scaling of GYSELA on CEA-HF



How to prepare GYSELA to HPC exascale architectures ?
→ Huge efforts of optimization and porting during EoCoE-II

E○C○E

- Target architectures:
  - 3 different architectures in the top 20

- Porting in 2021-2022 via CEA-RIKEN collaboration and GENCI support with ATOS

- Porting in 2022-2023 with HPE and EOLEN in the frame of ADASTRA Contrat de Progrès at CINES and with SCITAS-EPFL in the frame of EUROfusion Advanced Computing Hub

- May 2022: Opportunity to run during « Grand Challenge » campaign

TOP 500 The List. NOVEMBER 2022

Rank	System	Cores	Rpeak (Pflop/s)
2	**Supercomputer Fugaku** – A64FX 48C, Fujitsu - RIKEN Center for Computational Science – **Japan**	7,630,848	537.21
11	**Adastra** – HPE Cray, AMD Instinct MI250X GENCI-CINES – **France**	319,072	46.10
20	**CEA-HF** – BullSequana XH2000, AMD EPYC 7763, Atos – CEA – **France**	810,240	23.24

- Operator refactoring (collisions, sources) + Performance optimization at node level (vectorization, blocking, asynchronous MPI communications) → Gain > 70%

Impossible without HPC experts

⚠ Good performance on the 3 architectures with same Fortran code via OpenMP directives
→ Not feasible without rewritting, duplication of most of the kernels

Roadmap for GyselaX++ towards exascale

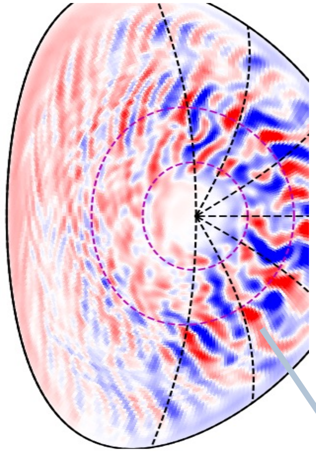
→ Why do we choose to rewrite GYSELA ?

- 20 years-old code written in Fortran with hybrid MPI/OpenMP parallelism
- Unique code for both CPU (AMD milan or ARM-A64FX) and GPU with OpenMP directives is NOT optimal → extremely difficult to optimize on all architectures.
- Non-equidistant mesh mandatory for core-edge-SOL turbulence simulations

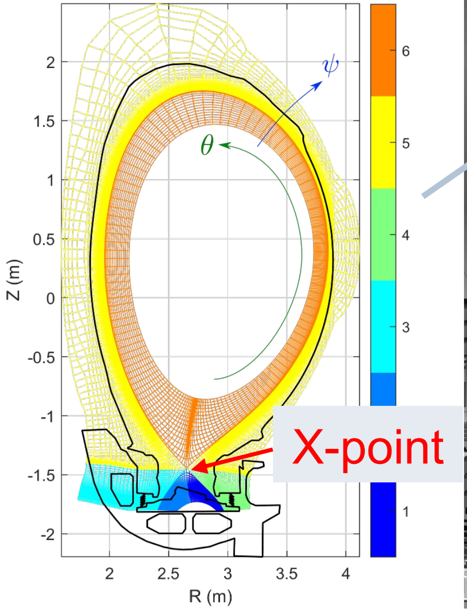
  → Modifying splines in GYSELA = rewrite most of the kernels
- X-point geometry

  → Development of new semi-Lagrangian scheme required to treat multipatches

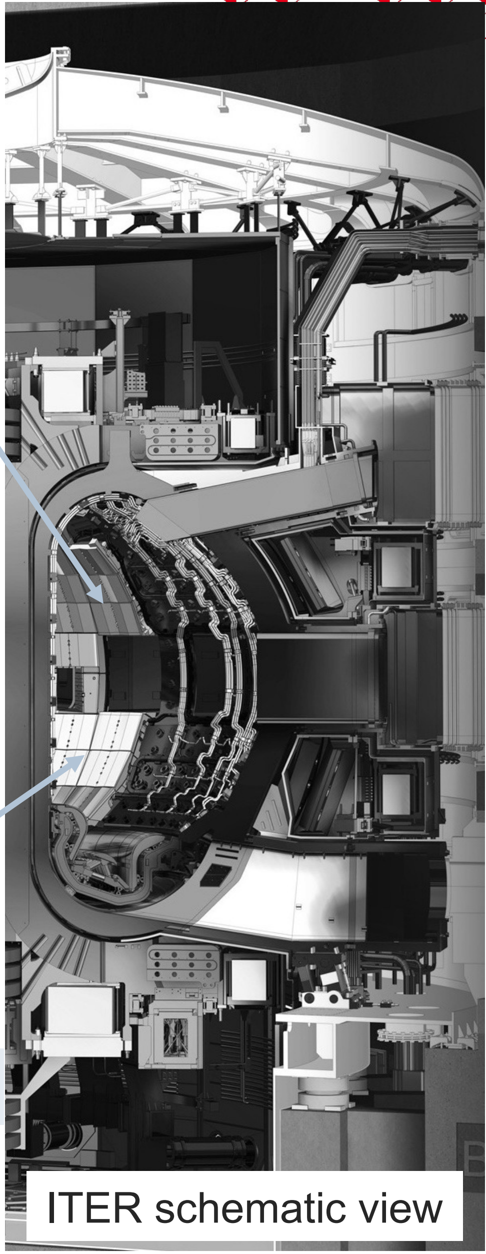
Simpler to rewrite main kernels in modern C++ from scratch
→ GyselaX++ code



GYSELA
D-Shape geometry



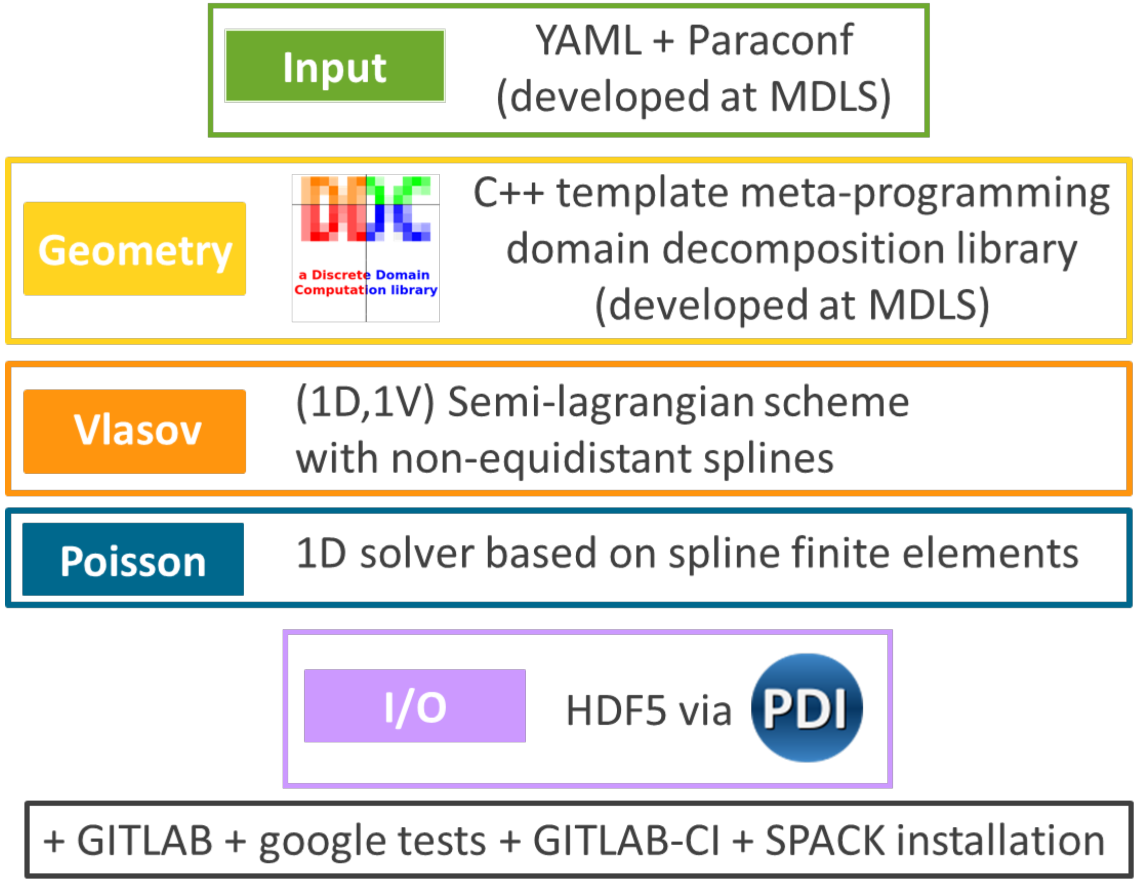
SOLEDGE-3X
X-point geometry



ITER schematic view

Gysela-X towards exascale
→ Complete rewriting of the code in modern C++ (1/2)

- Proof of Concept: 2D prototype VOICE++ in modern C++ to address plasma-wall interaction problem



Input — YAML + Paraconf (developed at MDLS)

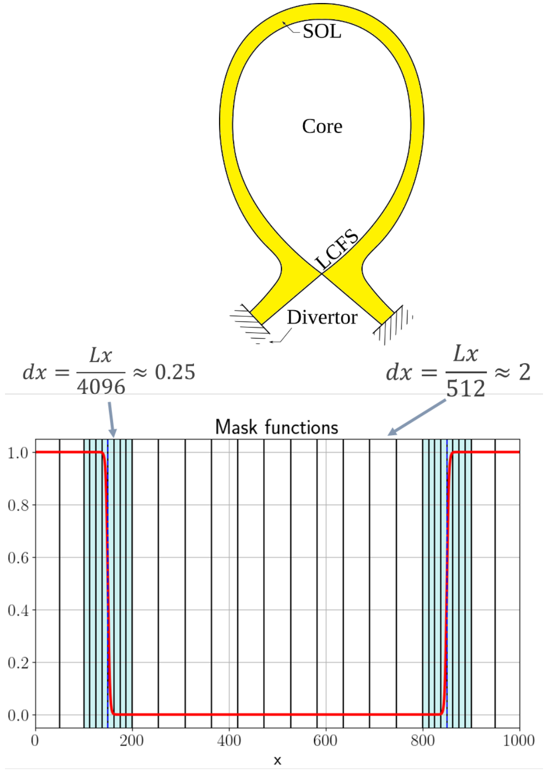
Geometry — a Discrete Domain Computation library — C++ template meta-programming domain decomposition library (developed at MDLS)

Vlasov — (1D,1V) Semi-lagrangian scheme with non-equidistant splines

Poisson — 1D solver based on spline finite elements

I/O — HDF5 via PDI

+ GITLAB + google tests + GITLAB-CI + SPACK installation



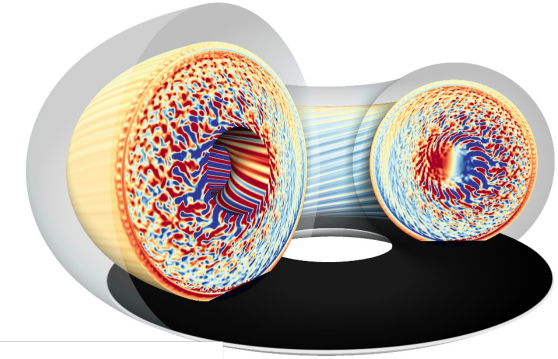
[E. Bourne et al., accepted JCP 2023]

[Y. Munschy et al., submitted to PoP]

https://github.com/gyselax/gyselalibxx

Gysela-X towards exascale
→ Complete rewriting of the code in modern C++ (2/2)

- 5D code in modern C++ scalable on exascale architectures



+

High level of parallelism MPI + KOKKOS

Input YAML + Paraconf (developed at MDLS)

Geometry DDC a domain decomposition library C++ template meta-programming domain decomposition library (developed at MDLS)

Vlasov **5D semi-lagrangian** scheme with non-equidistant splines

+ **Adding of all operators (gyroaverage + sources + collisions)**

Poisson **3D solver** based on 2D spline FEM + 1D

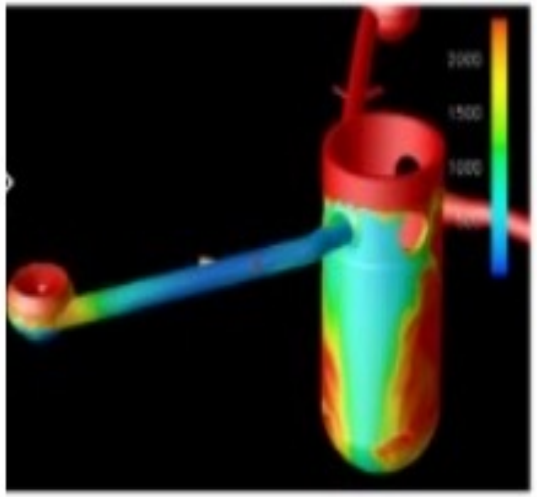
+ **Ampere** **(2D+1D) solver**

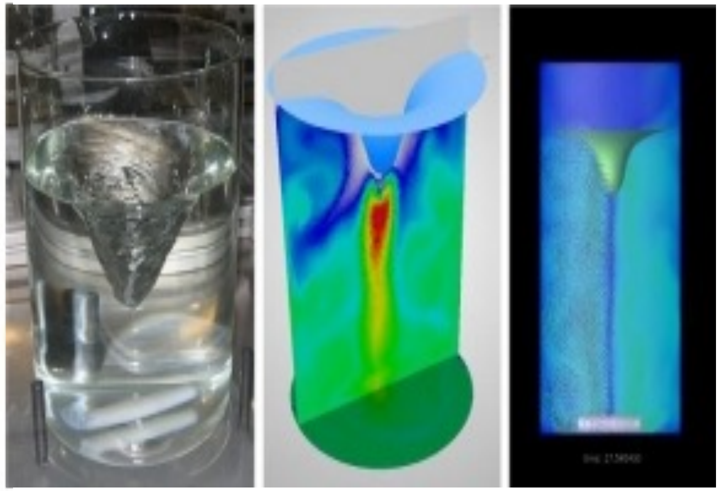
I/O **IMAS** via PDI

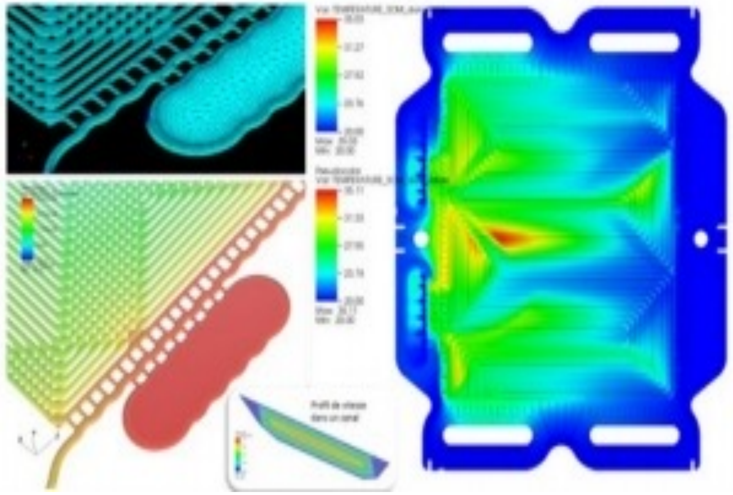
+ **In-Situ diagnostics**

+ GITLAB + google tests + GITLAB-CI + SPACK installation

The TRUST / TrioCFD application





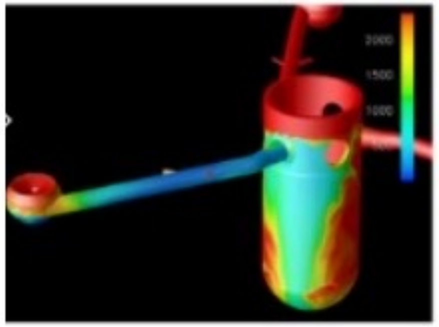


The TRUST/TrioCFD Application

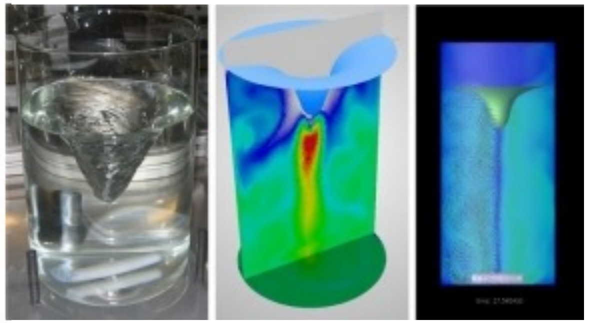
Thermohydraulic Plateforme (DES/DM2S/SGLS/LCAN)

Application dedicated to CFD build on TRUST

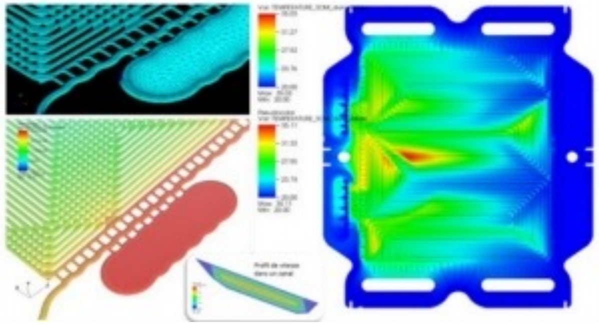
- Fluid mechanics :
  - Incompressible or slightly compressible;
  - Mono or diphasic
  - Front tracking
- Target applications area :



Reactor



Vortex Mixing



Fuel Cells

- C++, MPI, OpenSource HTTPS://github.com/cea-trust-platform
- Many other applications build on TRUST : FLICA5, STT, CATHARE3D, TrioIJK, TrioMC, GENEPI+, PAREX+,…

TRUST/TrioCFD roadmap for GPU computing

2014

- **First use of GPU in TRUST (PETSc)**
  - Single node GPU, limited to one solver (GMRES/Jacobi)

2020

- **Test AmgX, Nvidia GPU library**
  - Multi-node GPU, more solvers available (CG/Multigrid)
- **Porting of TRUST on ARM architecture**

2021

- **Add AmgX library (Nvidia) to TRUST (1.8.3)**
- **Nvidia Hackathon participation**

  Challenge TRUST team to evaluate OpenACC approach (parallel pragma directives)

2022

- **First study with a GPU partial accelerated TrioCFD (Jean-Zay)**
- **Partial port on AMD GPU with OpenMP on Adastra (GENCI contract)**

2023

- **First run with a fully GPU accelerated TRUST (Topaze)**

2024

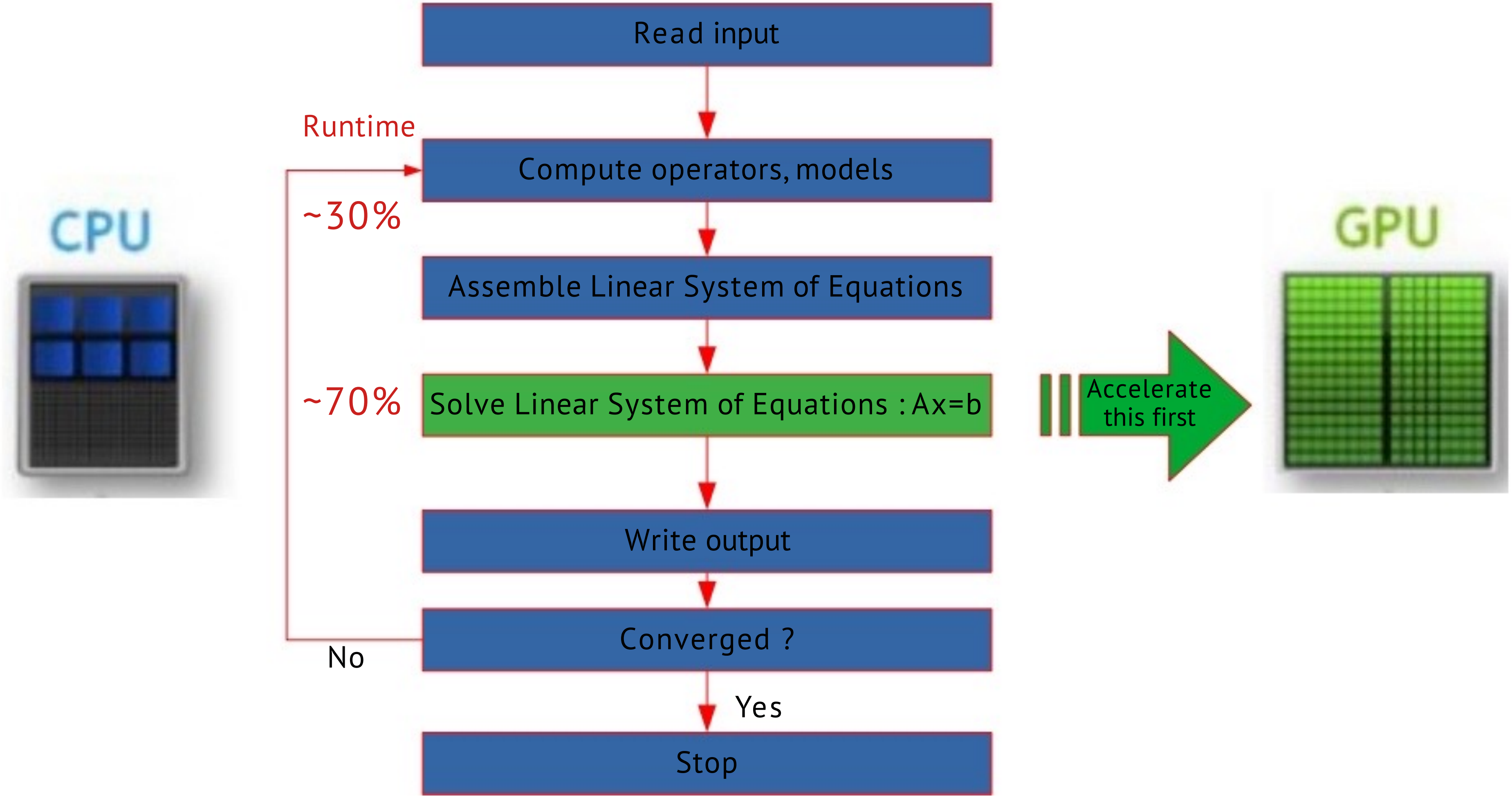
- **Enable CExA (Kokkos framework for CEA) in TRUST/TrioCFD**

2025

- **French exascale supercomputer (ARM CPU/Nvidia GPU?)**

Which strategy for TRUST computing on GPU ?

- Detect the most CPU expensive algorithms candidate to GPU



CPU

Read input

Runtime

Compute operators, models

~30%

Assemble Linear System of Equations

~70%

Solve Linear System of Equations : Ax=b

Accelerate this first

GPU

Write output

Converged ?

No

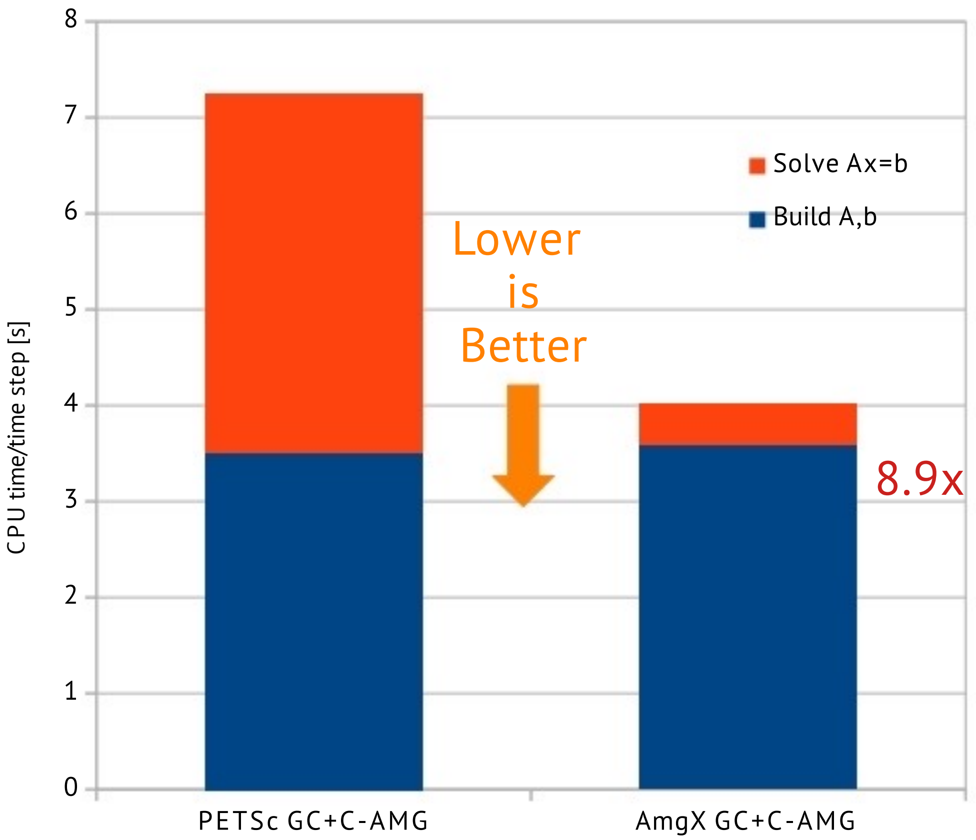
Yes

Stop

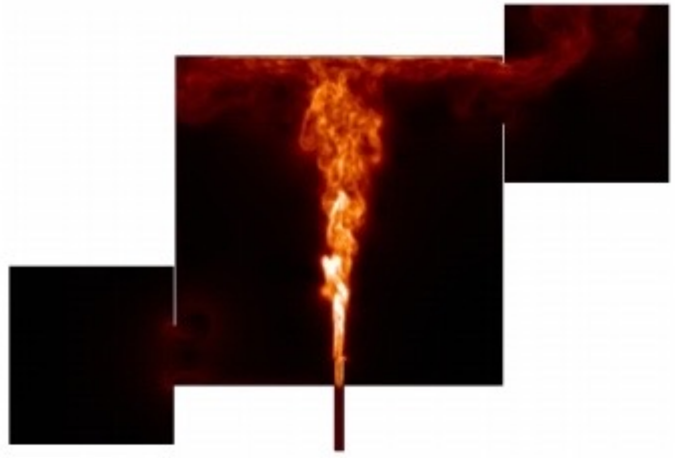
- Benefit firstly from dedicated linear algebra libraries (e.g. **AmgX** for GPU NVIdia)

Use of the AmgX solver (2021)

DNS simulation (TrioCFD 1.8.3) on Irene Joliot cluster (TGCC)



320 cores CPU 320 cores CPU + 32 GPU

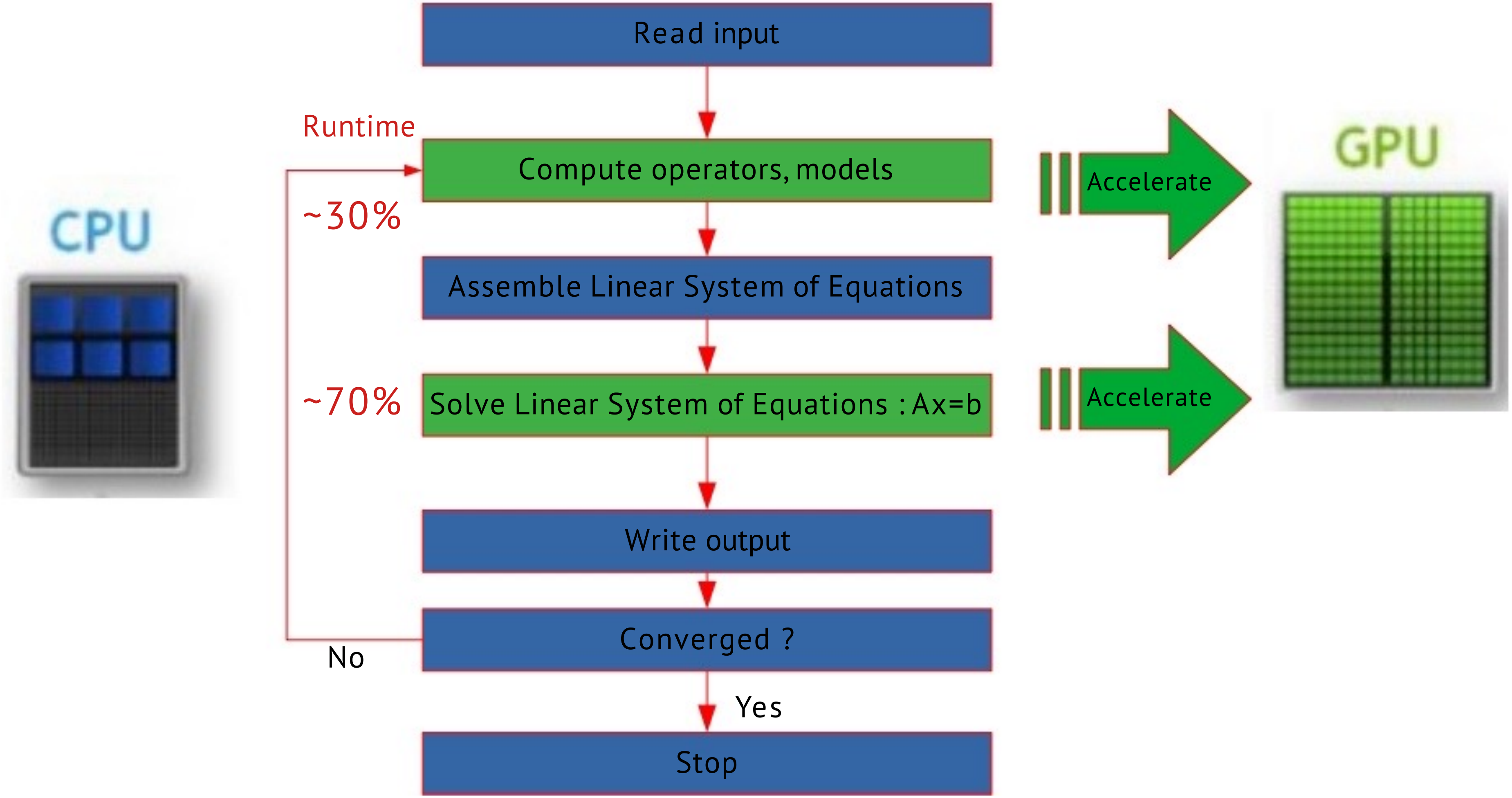


- Mini-GAMELAN geometry
- Structured mesh (VDF)
- 80M cells (250K/core)
- Unsteady DNS
- GC + C-AMG solver
- 50% time into solver

- 1.8x acceleration for the simulation

Which strategy for TRUST computing on GPU ?

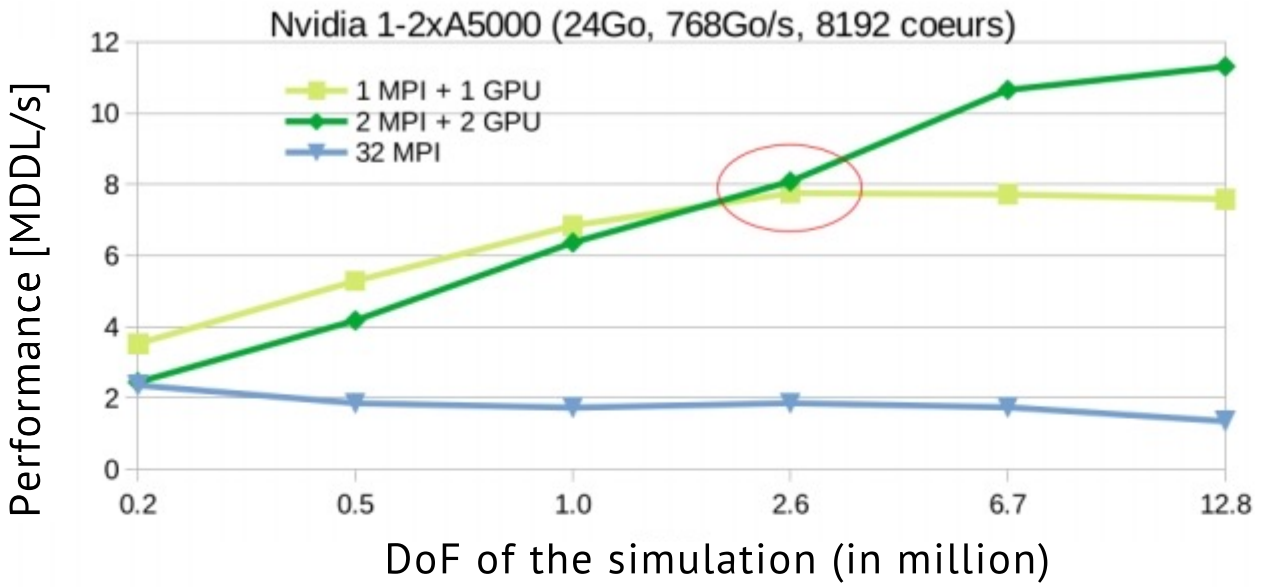
- Detect the most CPU expensive algorithms candidate to GPU


CPU
Read input
Runtime
Compute operators, models
~30%
Assemble Linear System of Equations
~70%
Solve Linear System of Equations : Ax=b
Write output
Converged ?
No
Yes
Stop
Accelerate
Accelerate
GPU

- Benefit from dedicated linear algebra libraries (e.g. **AmgX** for Nvidia, **rocALUTION** for AMD)
- Introduce parallel directives (**OpenMP**) for the the most CPU expensive loops

Lesson #1 : Go Big !!

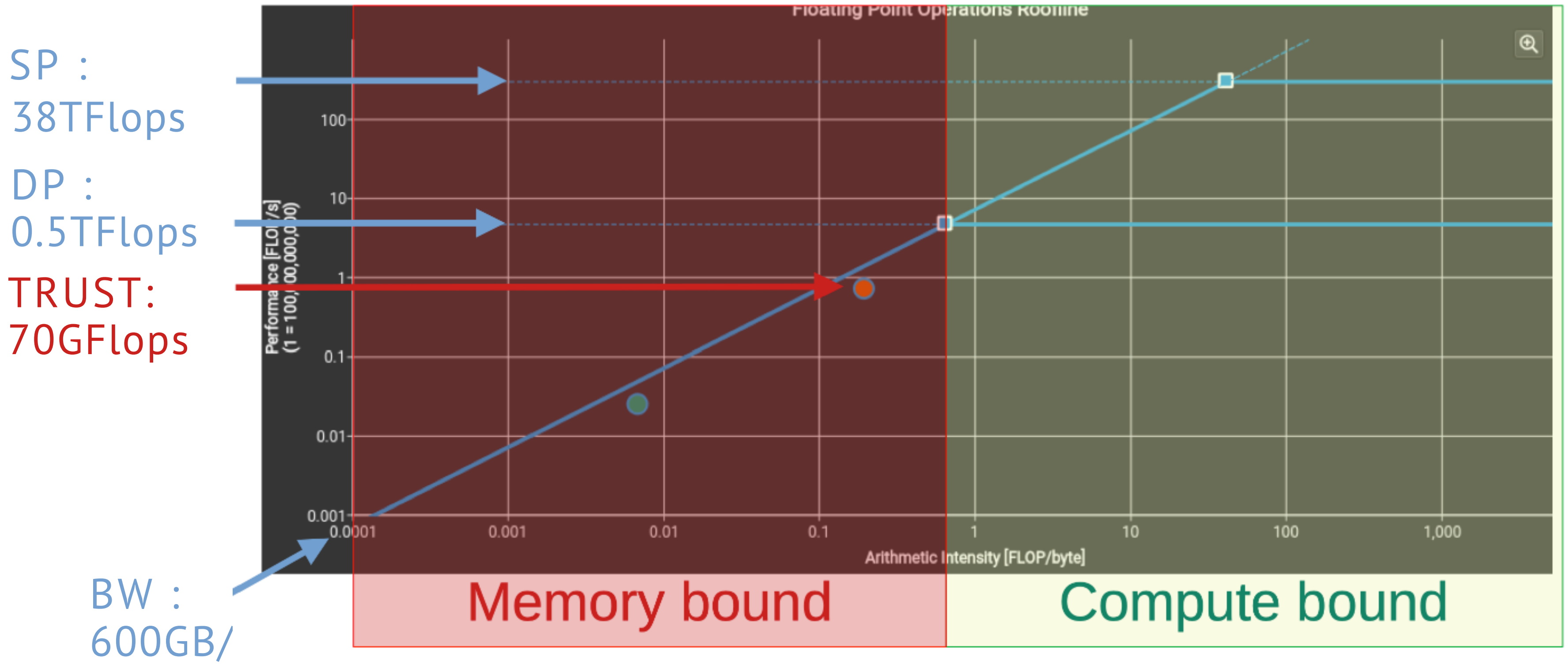
Higher is better



- GPU efficiency rise with the problem size
- 2-3 10^6 DoF per device seems optimal …
- … but it depends in the model, the device, communications,…

Lesson #2 : the code is memory bound

“roofline” analysis using Nsight Compute (Nvidia A6000):



SP : 38TFlops

DP : 0.5TFlops

TRUST: 70GFlops

BW : 600GB/

Memory bound

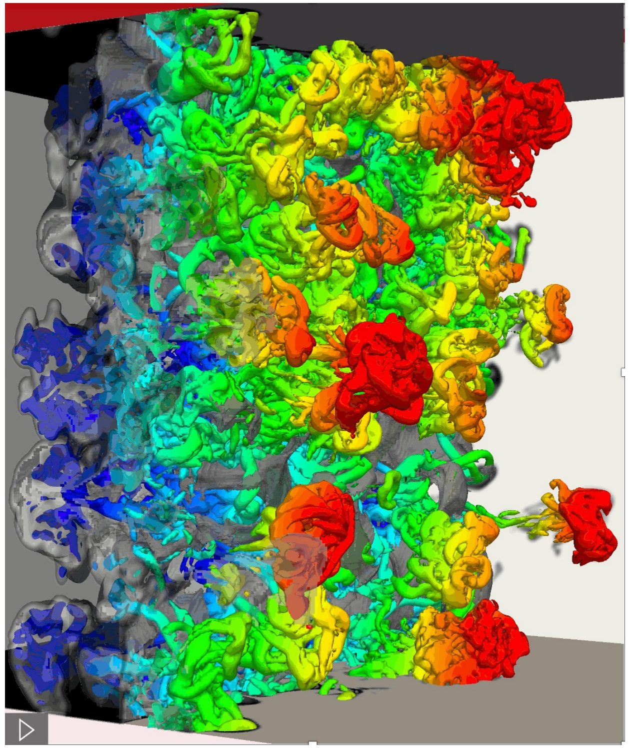
Compute bound

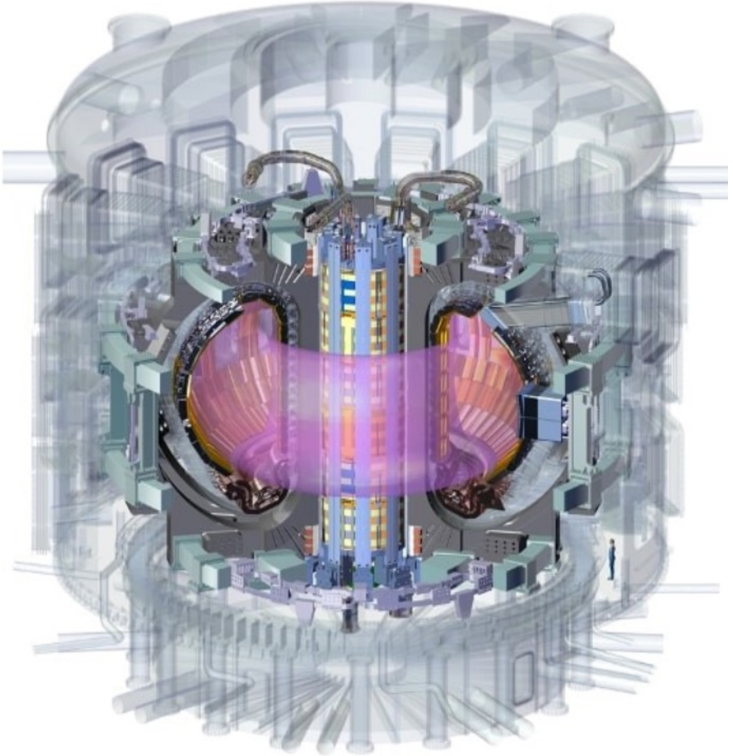
TRUST: Similar behavior on CPU and GPU

- The code is memory bound
- Only 15% of peak performance can be achieved on GPU

→ **Try to recompute some data instead of storing them**

The TRICLADE application



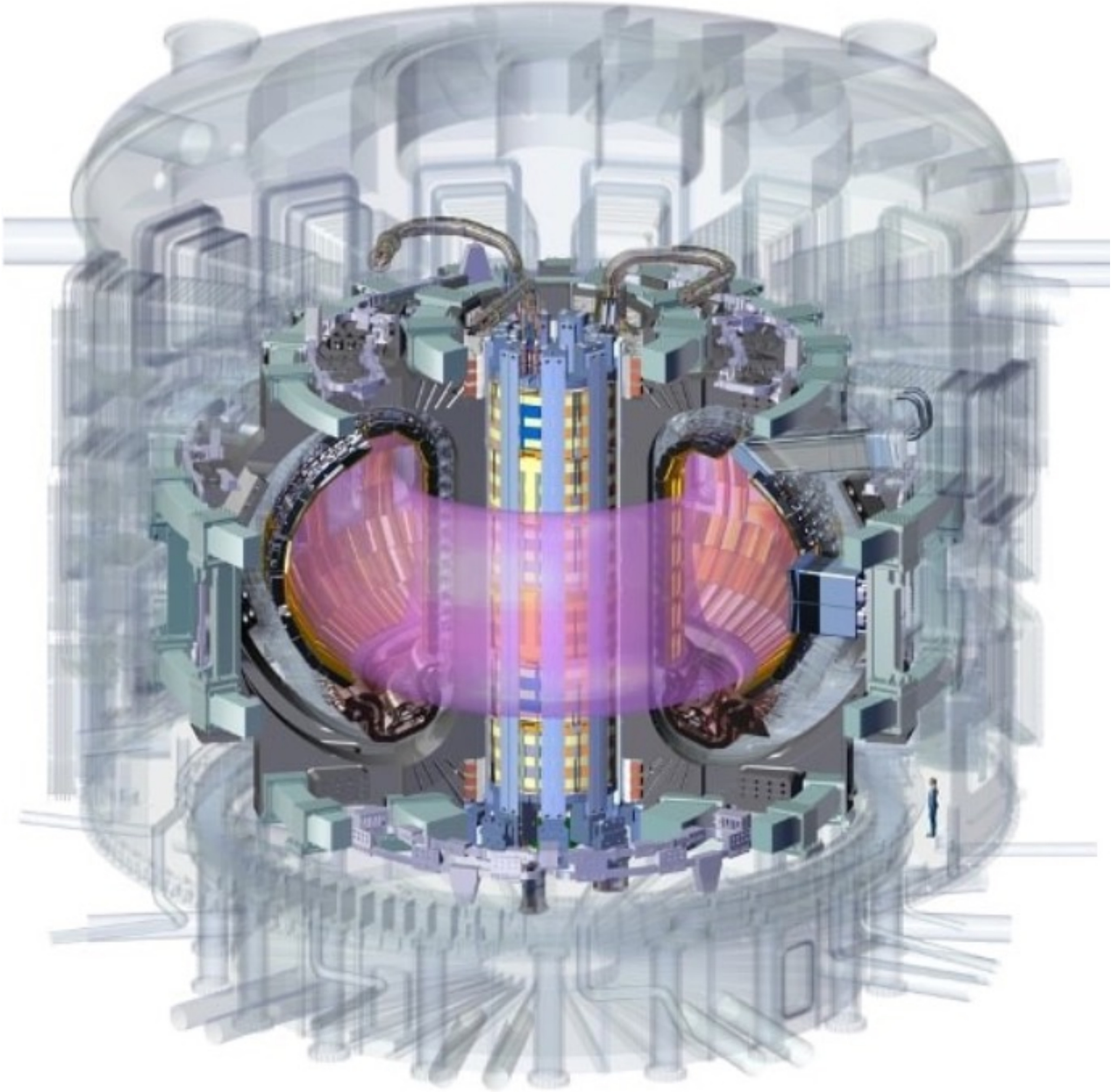


Introduction

Turbulent mixing

- Found in fields of interest to the CEA:
  - Astrophysics ;
  - Geophysics ;
  - Inertial Confinement Fusion ;
  - Etc.

- Very complex problem :
  - Intrinsically 3D ;
  - Multi-scale.

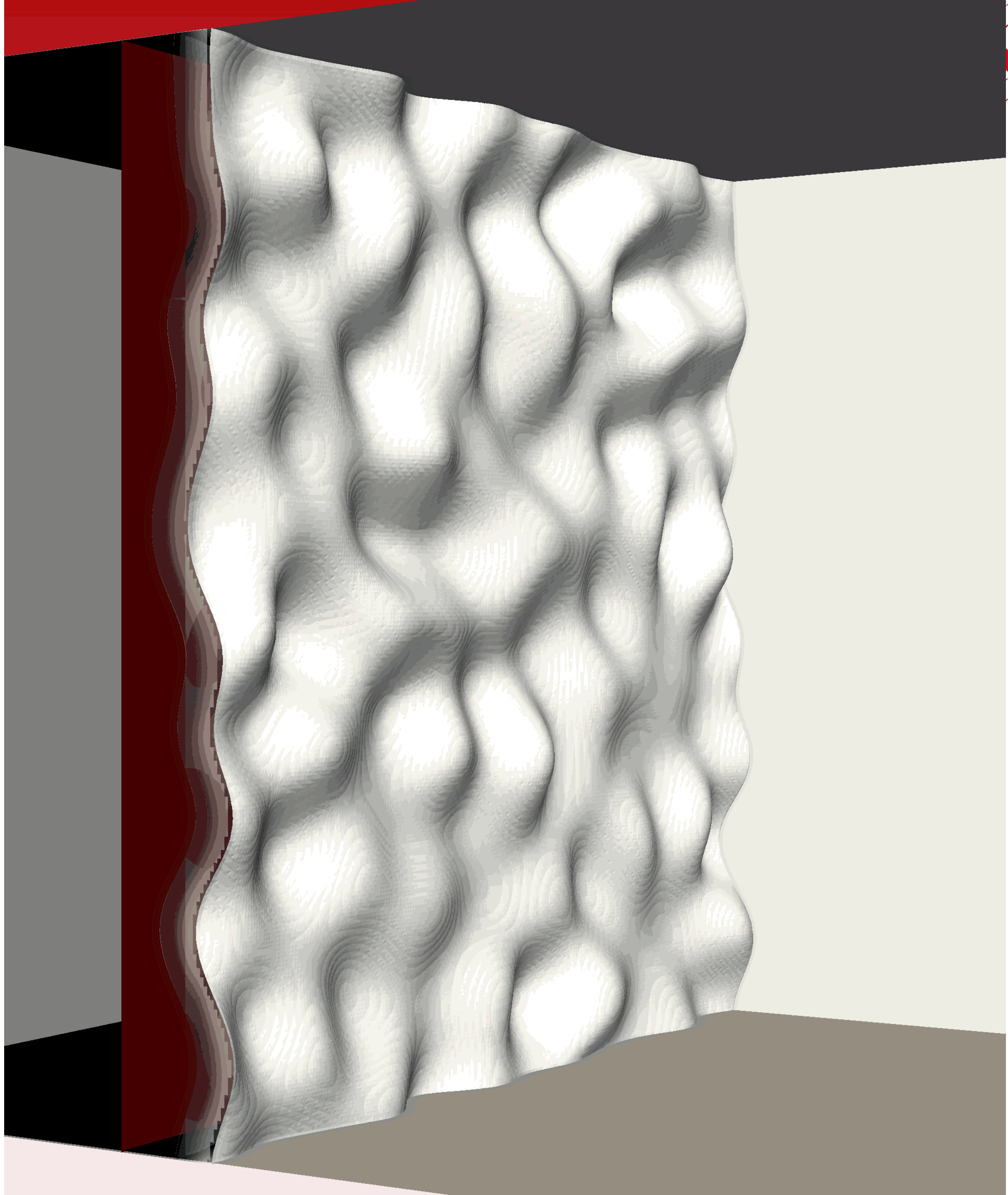


Some Context

- Study of Turbulent Mixing Zone:
  - Created and developed at fluids interface ;
  - From shock, expansion, acceleration, …
  - Dynamic and structure not fully understood.

- **TRICLADE**:
  - Turbulent binary mixing in a highly compressible environment
  - Navier-Stokes equations
  - Structured Cartesian Mesh
  - « Shock-capturing » numerical schemes

- Turbulence mixing problem = high complexity + multi-scale → need large mesh



Code information

- C++
  - Not really modern though…
  - ≈ 100 000 Lines of Code
  - MPI domain decomposition
  - Modular design
    - 1 module ≈ 1 numerical scheme
  - Depends on
    - Very little external libraries: MPI et FFTW
    - Lots of internal libraries for code environment

Porting Triclade to GPU

M5

Numerical scheme

Regardless of the CExA initiative

Triclade GPU port was decided

5th

Space order

3rd

Time order

Focusing on currently most use features

Impacted modules are roughly 10 000 LoC

few

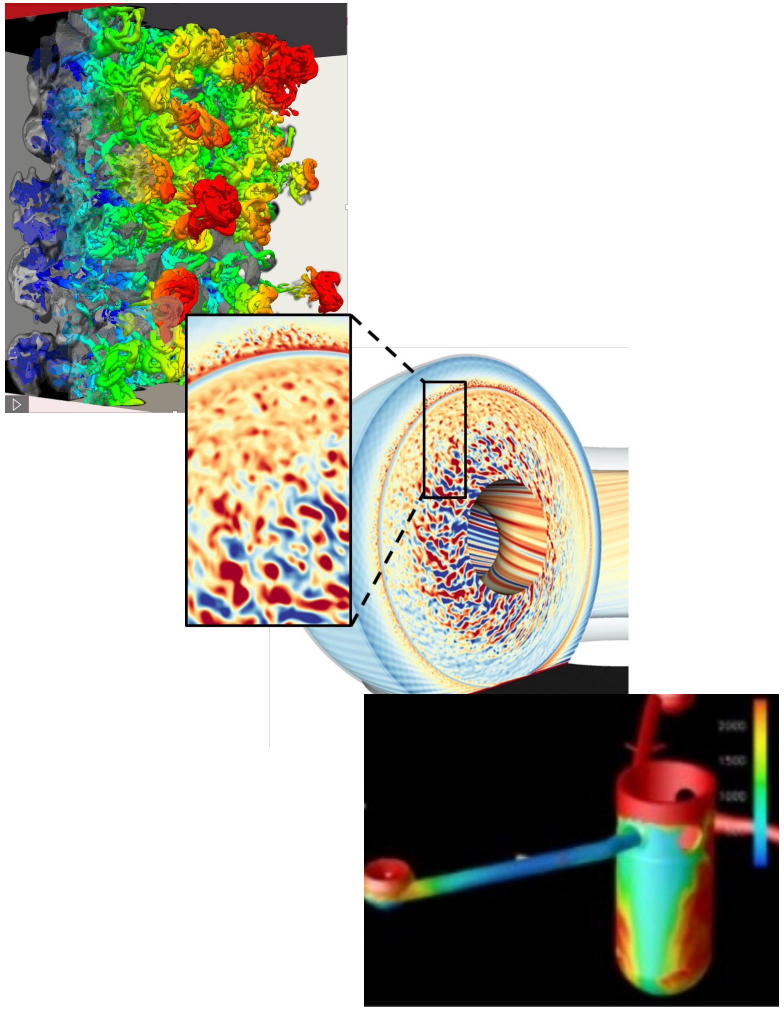
Limiters and extrapolation methods

hllc2

flux

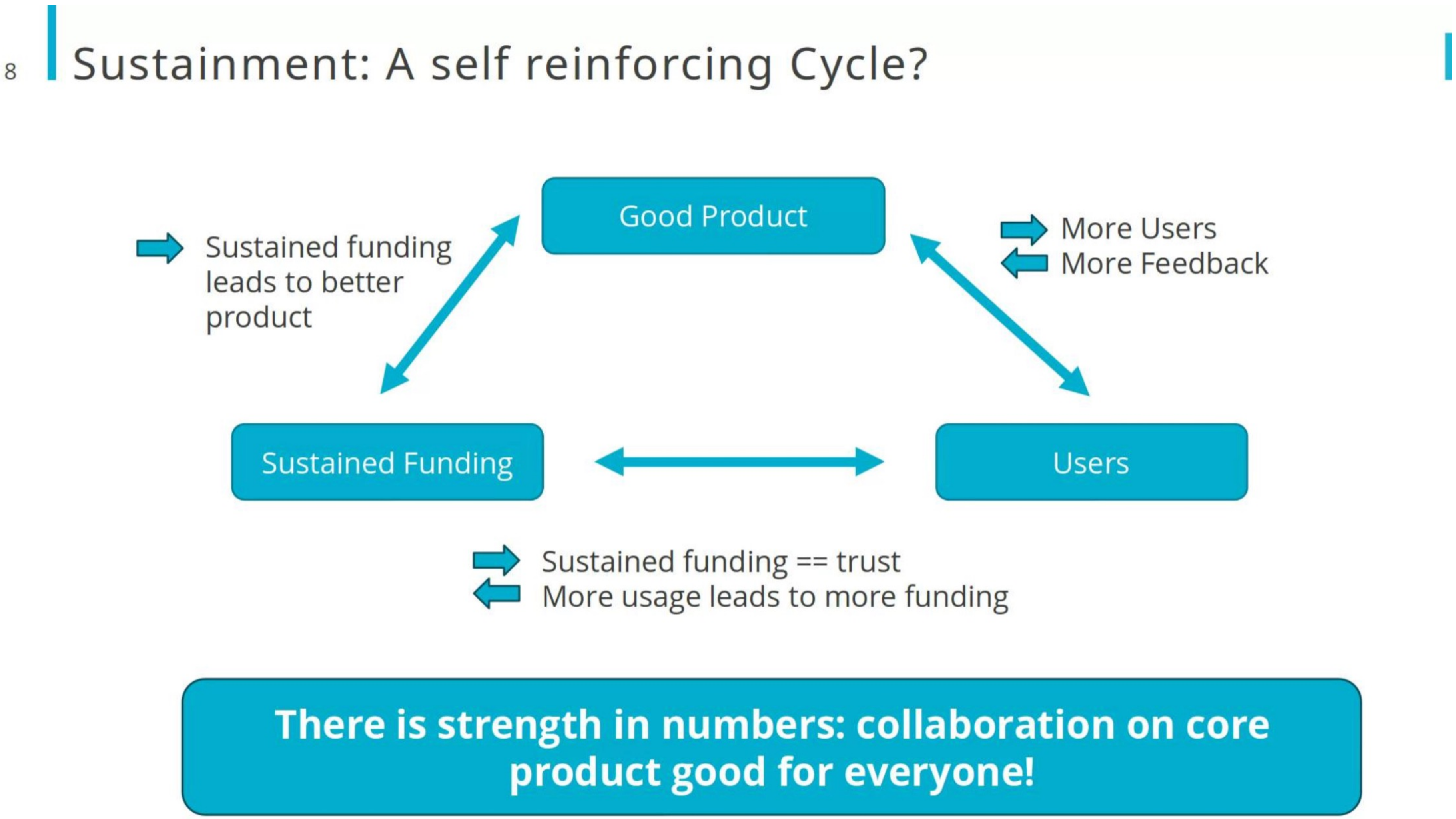
+ yet to be discovered dependencies...

Conclusion



- Efficient way to port applications to GPU
- Performance portability
- Leverage on the strength of the Kokkos community
- Feed back to the Kokkos core team
- Long term sustainability of the codes

Contribute to a virtuous circle !!



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Sustainment: A self reinforcing Cycle?

Good Product

Sustained Funding

Users

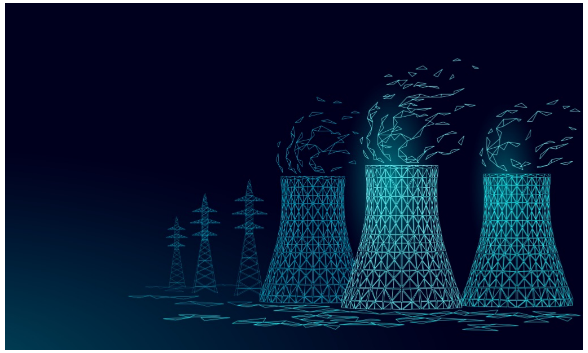
⇨ Sustained funding leads to better product

⇨ More Users
⇦ More Feedback

⇨ Sustained funding == trust
⇦ More usage leads to more funding

There is strength in numbers: collaboration on core product good for everyone!

Conclusion



- A sovereign tool to harness Exascale computers
- A large variety of applications across CEA
- CEA is building a community both around key applications and the Kokkos library development. The team is strongly motivated !!
- Strong collaboration with the Kokkos team
- A major impact on CEA programs and on many societal challenges
- Performance portability and code sustainability are the key challenges.
- Building a strong community is instrumental to meet the challenges
- Keep the application scientists onboard !

Thank you