Accelerating Fusion through Advancements in Edge Turbulence Modeling and its Integration in a Whole Device Model

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ECP EXASCALE COMPUTING PROJECT

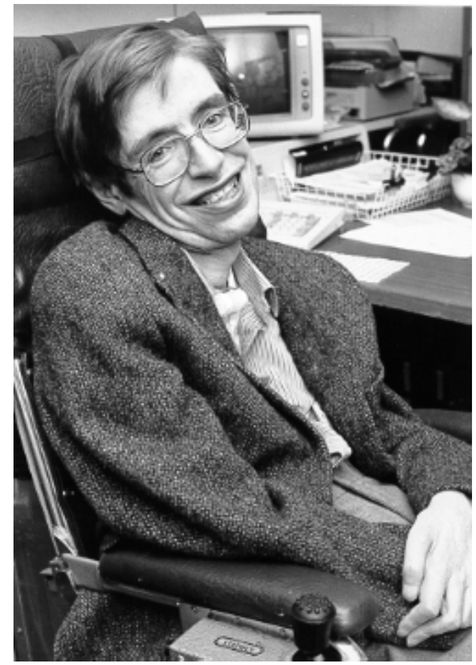
NNSA National Nuclear Security Administration

U.S. DEPARTMENT OF ENERGY | Office of Science

www.ExascaleProject.org

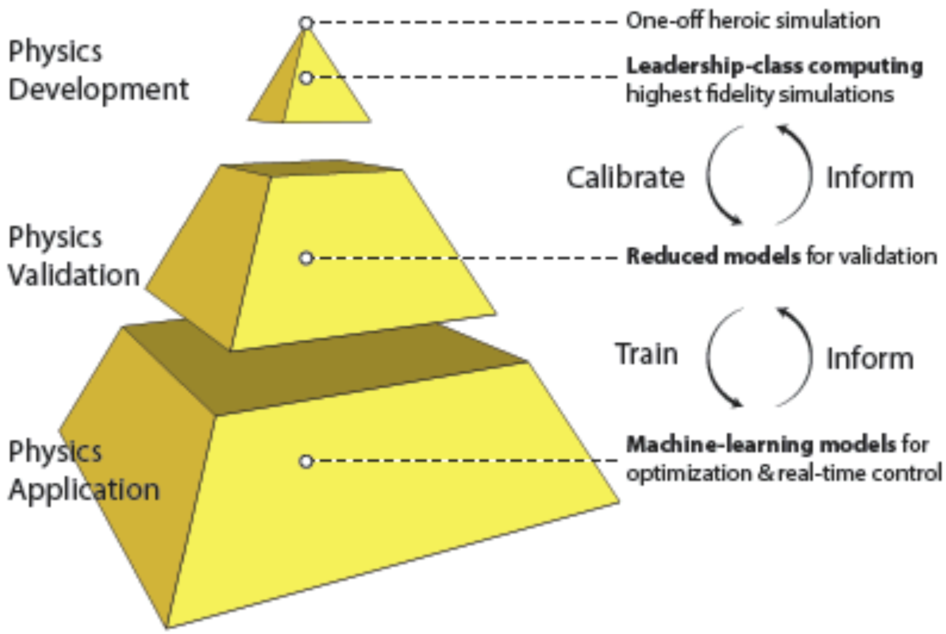
Grand Challenge : *Integration* of the knowledge provided by plasma models to understand, predict, and control the performance of fusion experiments

"I think the…21st century will be the century of complexity. We have already discovered the basic laws that govern matter and understand all the normal situations. We don't know how the laws fit together, and what happens under extreme conditions….There is no limit to the complexity we can build using those basic laws."----Stephen Hawking



1942-2018

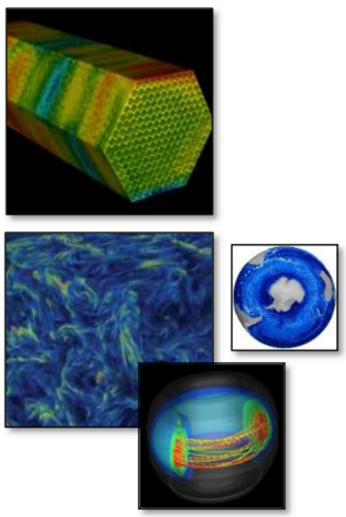
WDM hierarchy: High-fidelity to reduced models

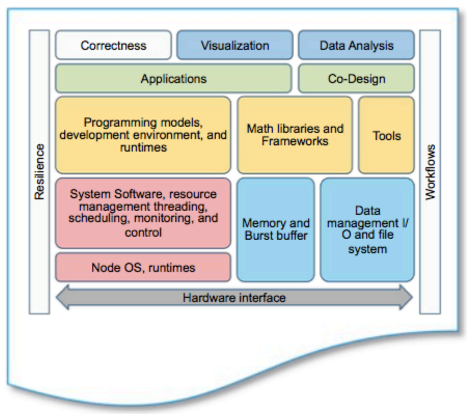


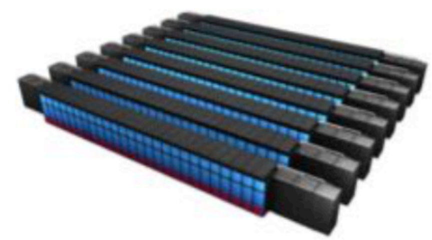
Courtesy: J. Candy

Exascale Computing Program: Holistic Approach (2016-23)

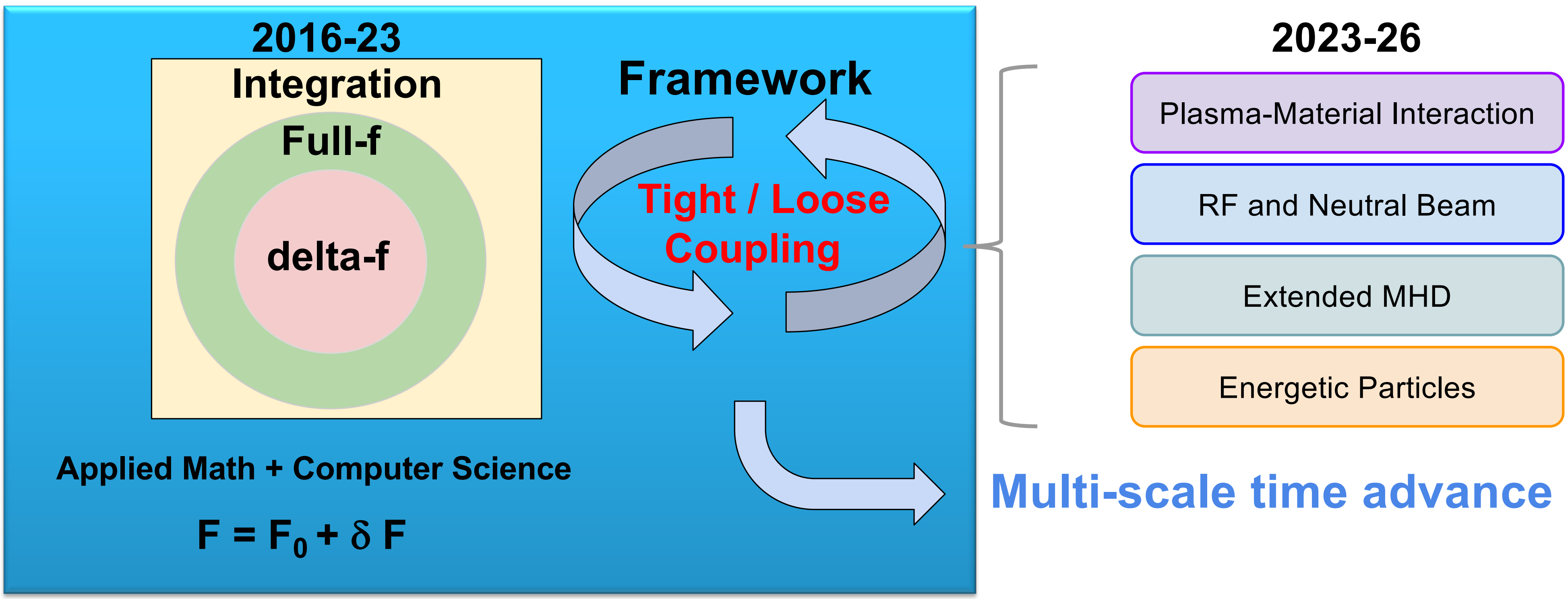
Application Development	Software Technology	Hardware Technology	Exascale Systems
Science and mission applications	Scalable software stack	Hardware technology elements	Integrated exascale supercomputers







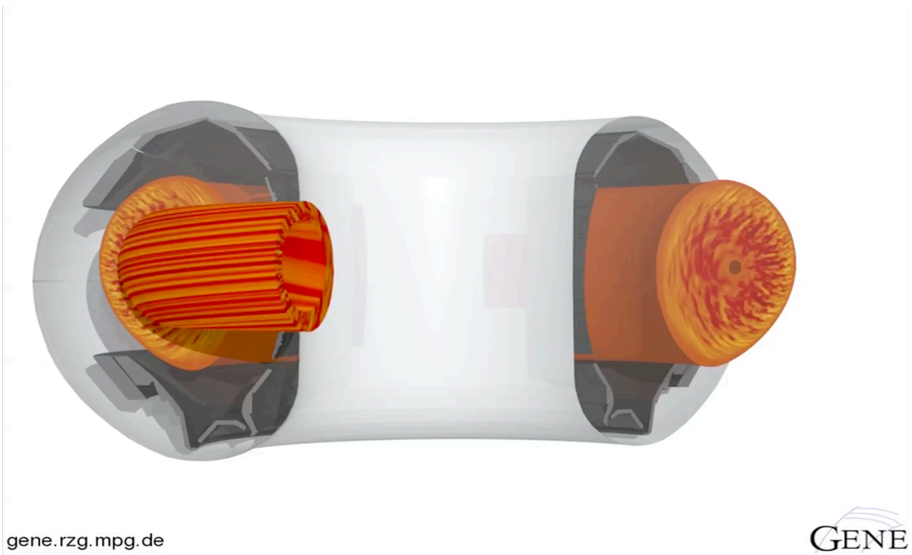
Vision: A High-Performant, First-Principles-Based Whole Device Model



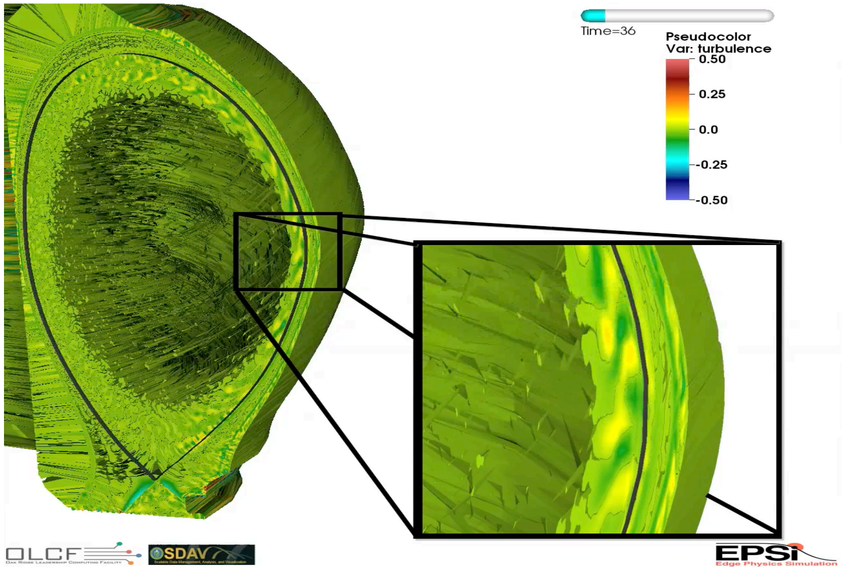
Coupling the core and edge: first in fusion history

The core evolves more slowly than the edge

Core Turbulence from GENE



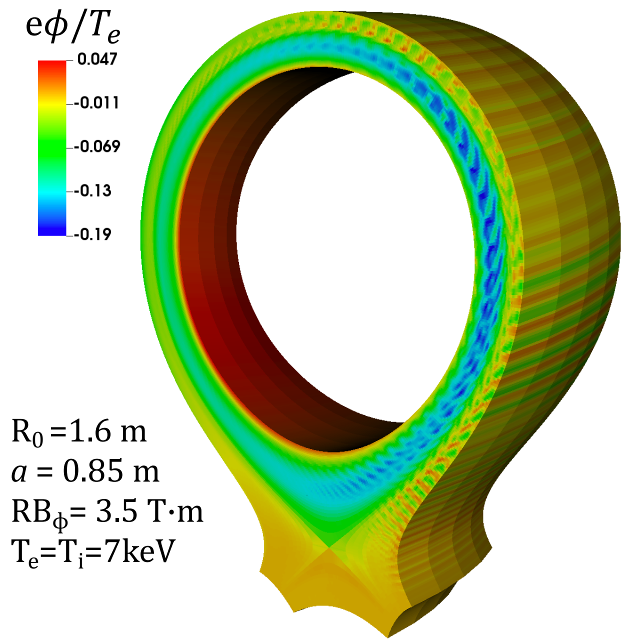
Edge Turbulence from XGC



Edge turbulence codes have undergone major advances

Cogent (LLNL)

- Solves full-f gyrokinetic equations for arbitrary number of species
- Employs 4th order conservative discretization and mapped multiblock grid technology
- Spatial grids aligned with magnetic field lines
- Fokker Planck collision operator
- Allows for options of coupling kinetic ions with fluid electrons or neutrals



Dorf and Dorr (2018, 2020)

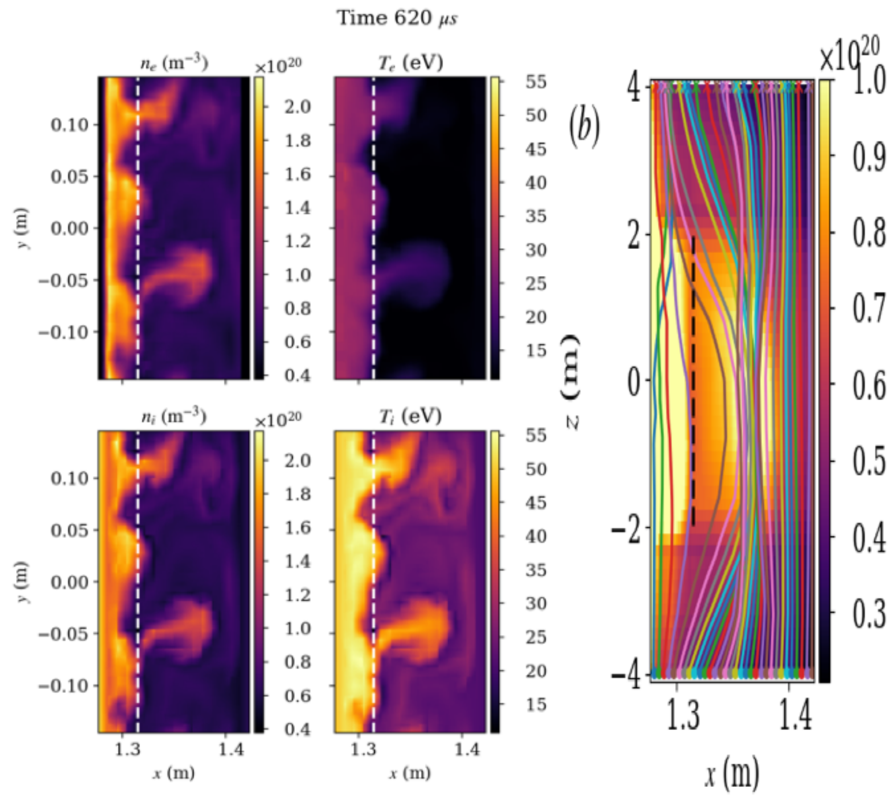
Cogent simulations of ITG turbulence in DIII-D

Edge turbulence codes have undergone major advances (continued)

Gkeyll (PPPL)

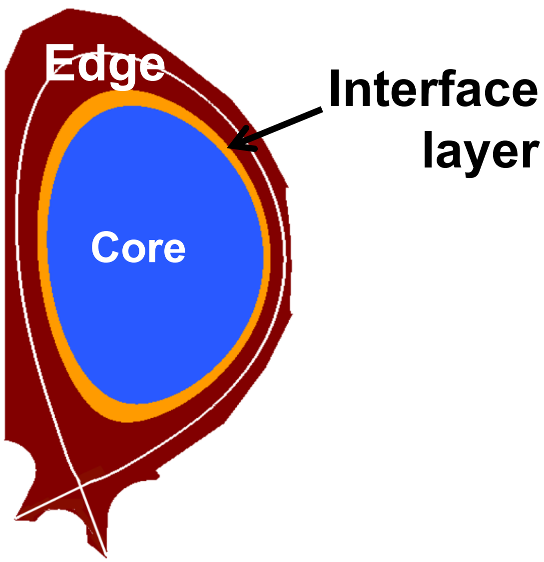
- Solves full-f gyrokinetic continuum equations
- Employs high-order discontinuous Galerkin scheme ensuring energy conservation (particles+fields)
- Fully electromagnetic including sheath boundary conditions (but does not yet include magnetic separatrix)
- Opensource

Mandell et al. (2020)



Gkeyll simulations of fully em turbulence of helical SOL plasma

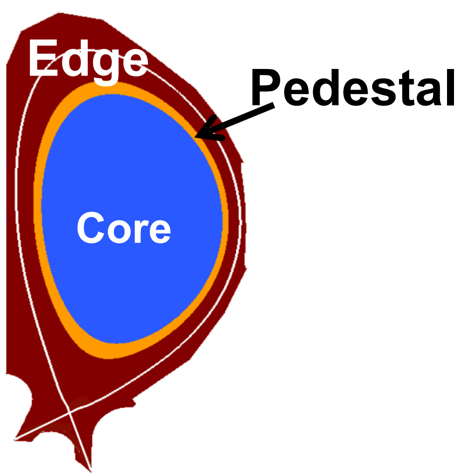
Principal WDMApp Goals



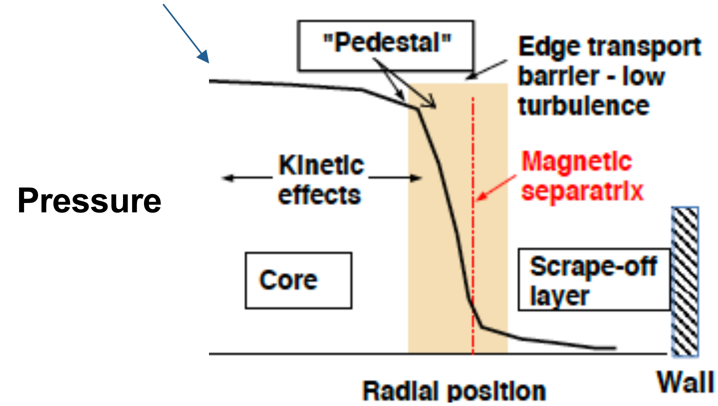
- Demonstration and assessment of WDM **gyrokinetic physics** on experimental transport time-scale in a challenge problem for pedestal formation
- **Figure of Merit (FOM) of >50** for coupled code on exascale platforms, accomplished through algorithmic advancement, performance engineering and hardware improvement
- Completion of **extensible integration framework** EFFIS 2.0 (End-to-End Framework for Fusion Integrated Simulations 2.0) and demonstration on exascale platform

WDMApp Challenge Problem

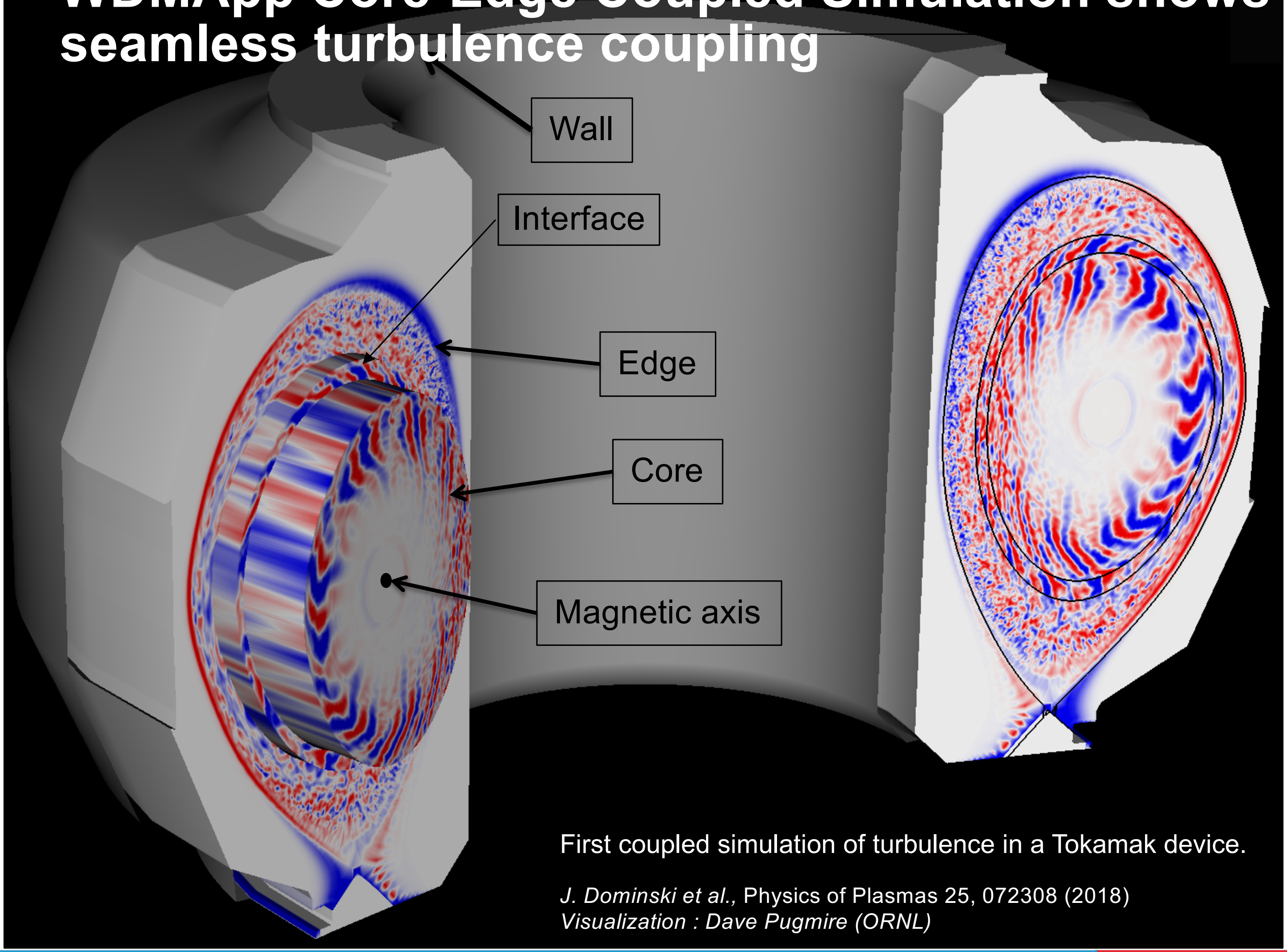
High-fidelity simulation of a whole-device burning plasma (specifically, ITER with full plasma current) operating in “high-mode” (H-mode), and prediction of the plasma pressure “pedestal” shape (height and width)



Pedestal determines the plasma pressure, hence fusion yield, in the burning core



WDMApp Core-Edge Coupled Simulation shows seamless turbulence coupling



First coupled simulation of turbulence in a Tokamak device.

J. Dominski et al., Physics of Plasmas 25, 072308 (2018)
Visualization : Dave Pugmire (ORNL)

Developing core-edge coupling of technology

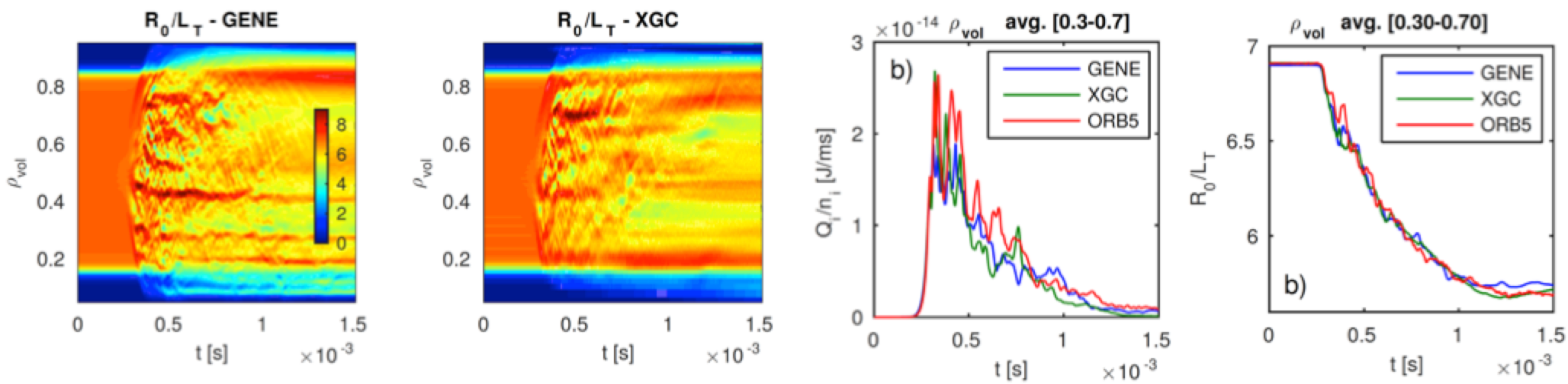
1. We first use XGC-XGC coupling to develop the technology
2. Apply the technology to GENE/GEM and XGC coupling

XGC is the leading gyrokinetic code for simulating edge region, including a separatrix.

GENE and GEM are leading gyrokinetic codes for simulating core region.

Cross-verification between GENE and XGC:

Non-linear ITG instability (J. Dominski, S. Ku, G. Merlo, C.S. Chang, F. Jenko, S. Parker)



Time-radius dynamics of the logarithmic gradient $R_{o/}L_T$

Excellent agreement in the time-evolution of the global ion heat flux and temperature gradient. Radial average is taken over the widest region (0.3-0.7) after removing the simulation-boundary area.

Core-edge coupling

Coupling of XGC-core and XGC-edge

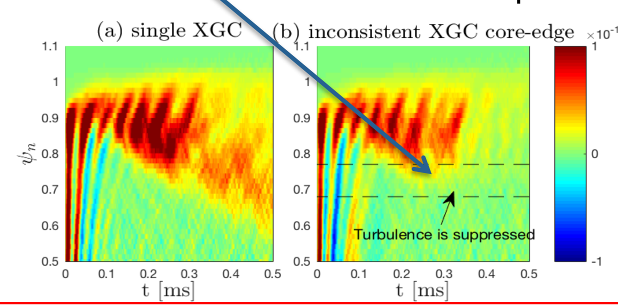
Implemented by J. Dominski, S.H. Ku, and C.S. Chang.

- True kinetic coupling between executables
- The coupled simulation is statistically equivalent to the reference simulation
- Study how to replace the XGC core simulation with a GENE simulation

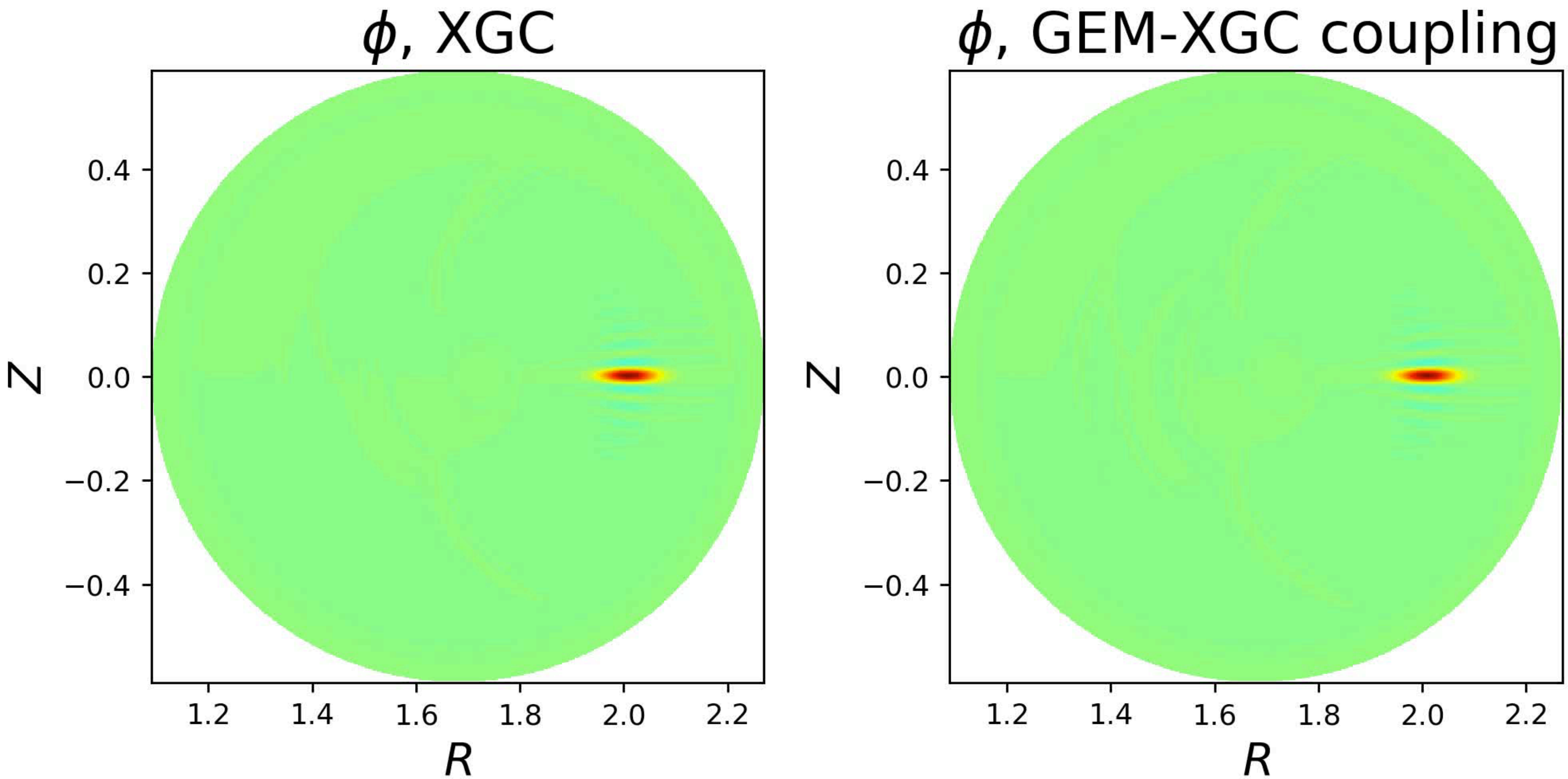
Difficulty was in avoiding turbulence suppression from nonlinear de-phasing between two codes.

Failed example

Ion heat flux, Qi

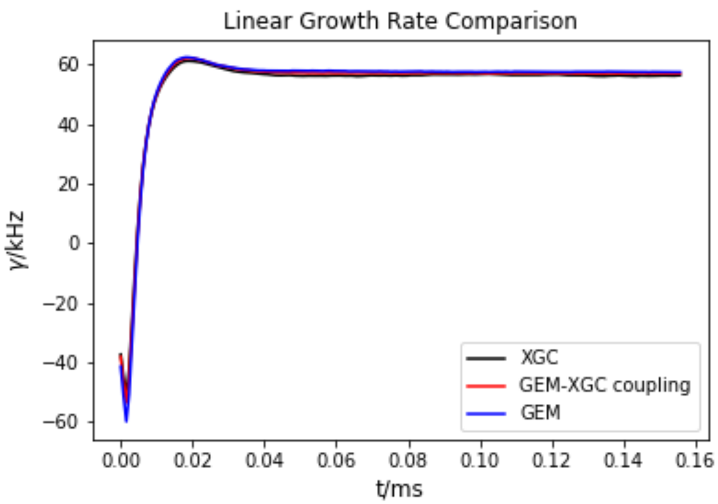


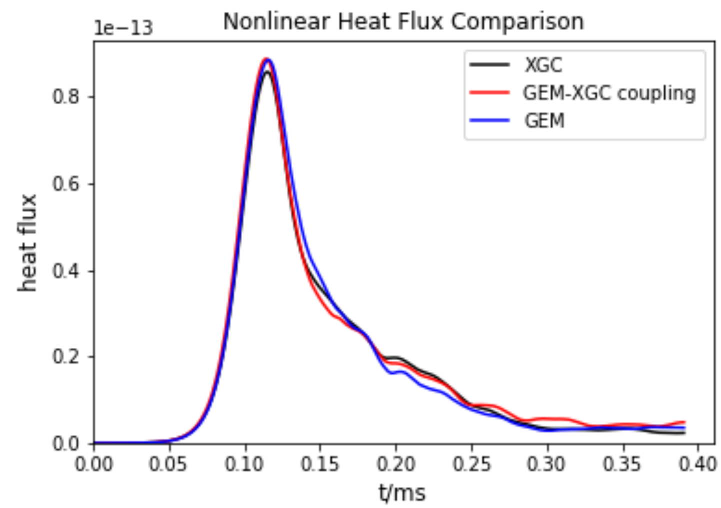
XGC – GEM coupling



WDMApp coupling results

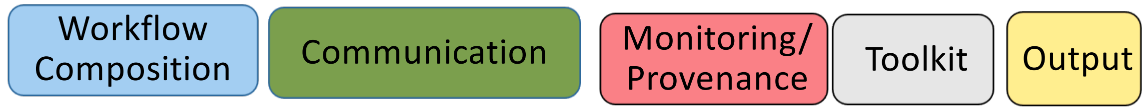
- Linear results (n=24): frequency almost the same, growth rate differs ~1%, between coupled code and XGC reference
- Nonlinear results (n=3,6,9,12…) show ~4% difference for the saturation level of heat flux, between coupled code and XGC reference
- Coupled code adds little cost when using parallelized grid-quantity mapping (algorithm and performance enhancement). For example, 24.62s for XGC only, 25.23s for coupling with parallelized mapping.



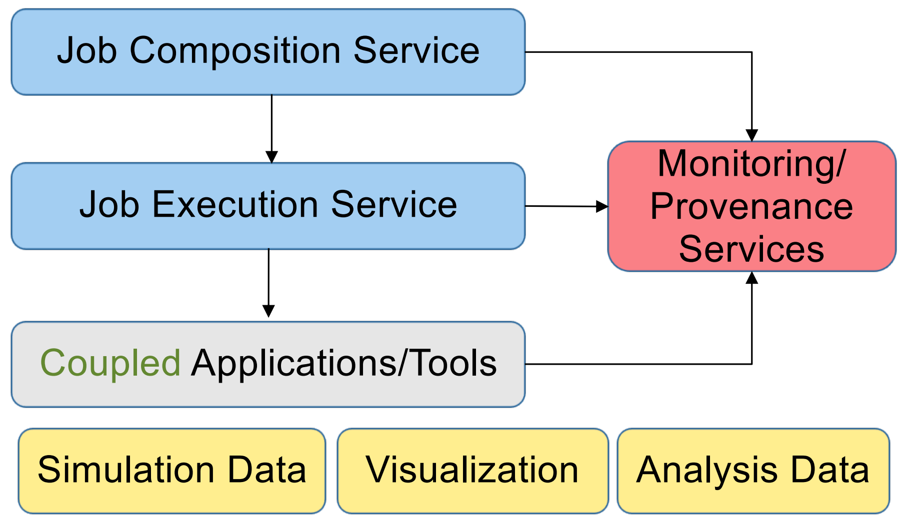


GENE-XGC Coupling

What is EFFIS 2.0?



- EFFIS 2.0 is a workflow coordinator for the WDM App
  - A collection of services to compose, launch, monitor, and communicate between coupled applications
  - Automates "easy" deployment on DOE systems
  - Facilitates "easy" integration to analysis and visualization tools, components, frameworks, etc.
  - Unique features: in-situ memory-based data movement, placement options (e.g. same node), wide-area network, automated visualization



Optimization of GENE, XGC and GEM for large-scale Summit

ECP WBS	ADSE12-16 WDMApp
PI	Amitava Bhattacharjee, PPPL
Members	PPPL, ORNL, ANL, LBNL, UNH, UT-Austin, UC-Boulder

Scope and objectives

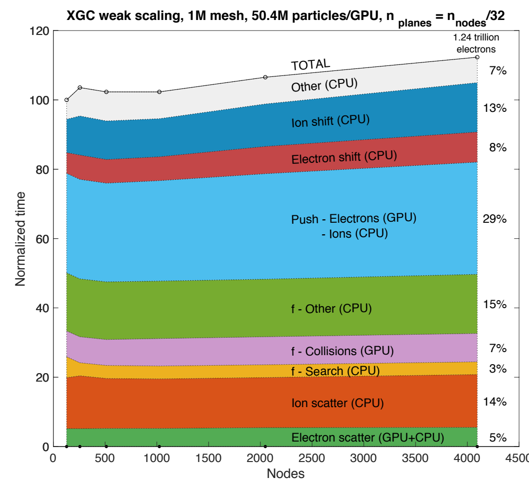
- Port and optimize WDMApp codes on Summit computer in preparation for exascale systems
- Leverage the ECP Co-Design and Software Technologies projects for portability and performance
- Scale WDMApp codes GENE, XGC, and GEM to 20% of Summit

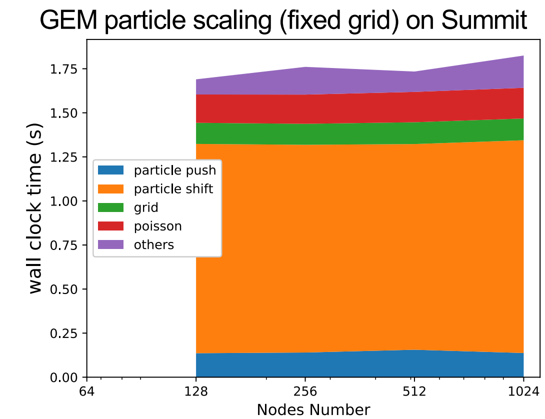
Impact

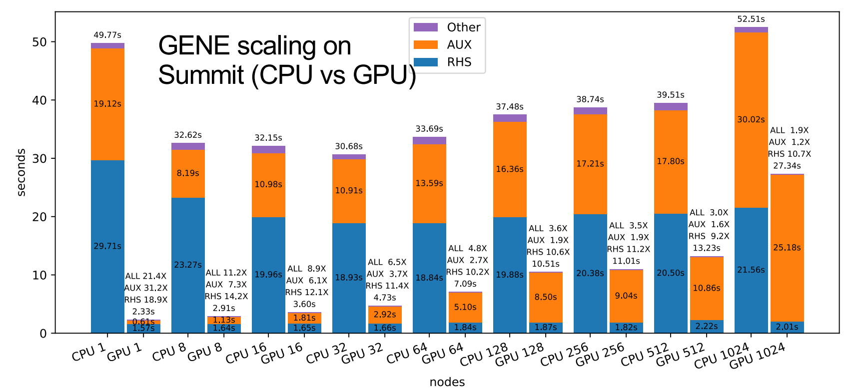
- Achieving high performance and scalability on a multi-GPU system is a critical requirement towards running WDMApp on Frontier and Aurora

Project accomplishments

- Successful porting to GPU of all three codes used in the WDM application: XGC, GENE, and GEM
- Use of CoPA-developed “Cabana” library in XGC, leading to high portability without loss of performance or scalability
- All 3 codes successfully ran on 1,024+ nodes on SUMMIT







Conclusions

- WDMApp is a leading priority of the fusion community and will deliver a computational tool of unprecedented power and versatility.
- We have focused here on two primary goals: (1) Coupling of core gyrokinetic code (GENE and GEM) and edge gyrokinetic code (XGC), and performance of the coupled code with FOM > 50 (2) Development of a user-friendly extensible framework EFFIS 2.0 for code-coupling in WDMApp.
- The science is potentially transformational, and compute power will help realize Hawking's vision for fusion in the 21st century.