GYRO: A 5-D gyrokinetic-Maxwell solver

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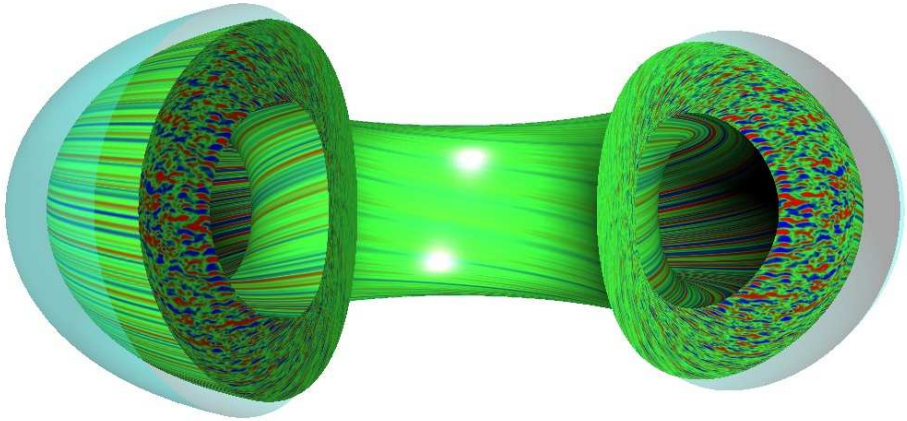


GYRO Overview

- 5D Eulerian gyrokinetic-Maxwell (GKM) solver developed by Jeff Candy and Ron Waltz at General Atomics
- Computes the turbulent radial transport of particles and energy in tokamak plasmas
- Electron parallel motion treated implicitly, and other dynamics explicitly, using Implicit-Explicit (IMEX) Runge-Kutta time-integration scheme
  - Discretized on an Eulerian grid
- Only GKM code with both *global* and *electromagnetic* capabilities
  - Radially global: able to accomodate arbitrary profile variation
  - Electromagnetic fluctuations with real electrons ($m_i/m_e = 3600$)
- Toroidally spectral (single-n to full torus)
  - Can switch between global and flux-tube operational modes

Comparison with other GK codes

Code	Laboratory	Type	Local	Global	Elec	Shape
GS2	U. Maryland	Euler	•		•	•
GYRO	General Atomics	Euler	•	•	•	•
GTC	PPPL/UCI	PIC		•		
TUBE	U. Col at Boulder	PIC	•		•	
PG3EQ	LLNL	PIC	•			

where PIC=particle-in-cell, Euler=Eulerian, Elec=Electromagnetic, PPPL=Princeton, UCI=U. California at Irvine, and LLNL=Lawrence Livermore National Laboratory

Portable

- GYRO compiles and runs on
  - laptops
  - Linux clusters at GA and PPPL
  - Power3 clusters at NERSC, SDSC, and ORNL
  - Power4 at ORNL
  - SGI Altix at ORNL
  - Cray X1 at ORNL
- Just set an environment variable
- Balanced performance on all architectures

GYRO accomplishments on the X1

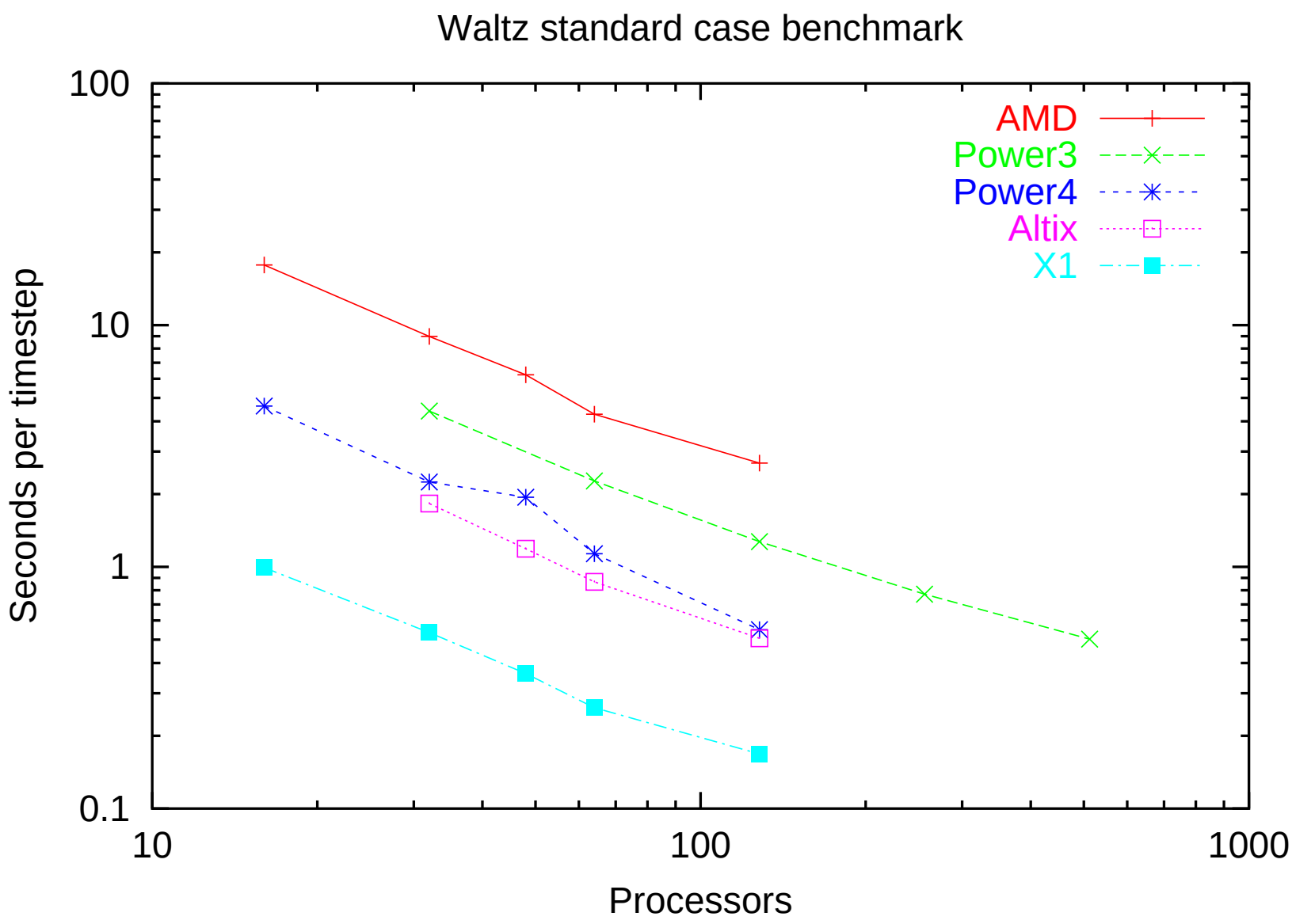
Several new findings enabled by increased computing capability!

- **An exhaustive series of global, full-physics GYRO simulations of DIII-D L-mode ρ_*-similarity discharges was made:**
  - calculations matched experimental results for electron and ion energy transport [1] within experimental error bounds
  - Bohm-scaled diffusivity of the experiments was also reproduced
  - **the most physically comprehensive tokamak turbulence simulations ever undertaken**
- **showed that a minimum-q surface in a tokamak plasma does not act as the catalyst for ion transport barrier formation [4]:**
  - there are theories in the literature that argue a barrier should form near $s = 0$
  - it was clearly shown that transport is smooth across an $s = 0$ surface due to the appearance of *gap modes*

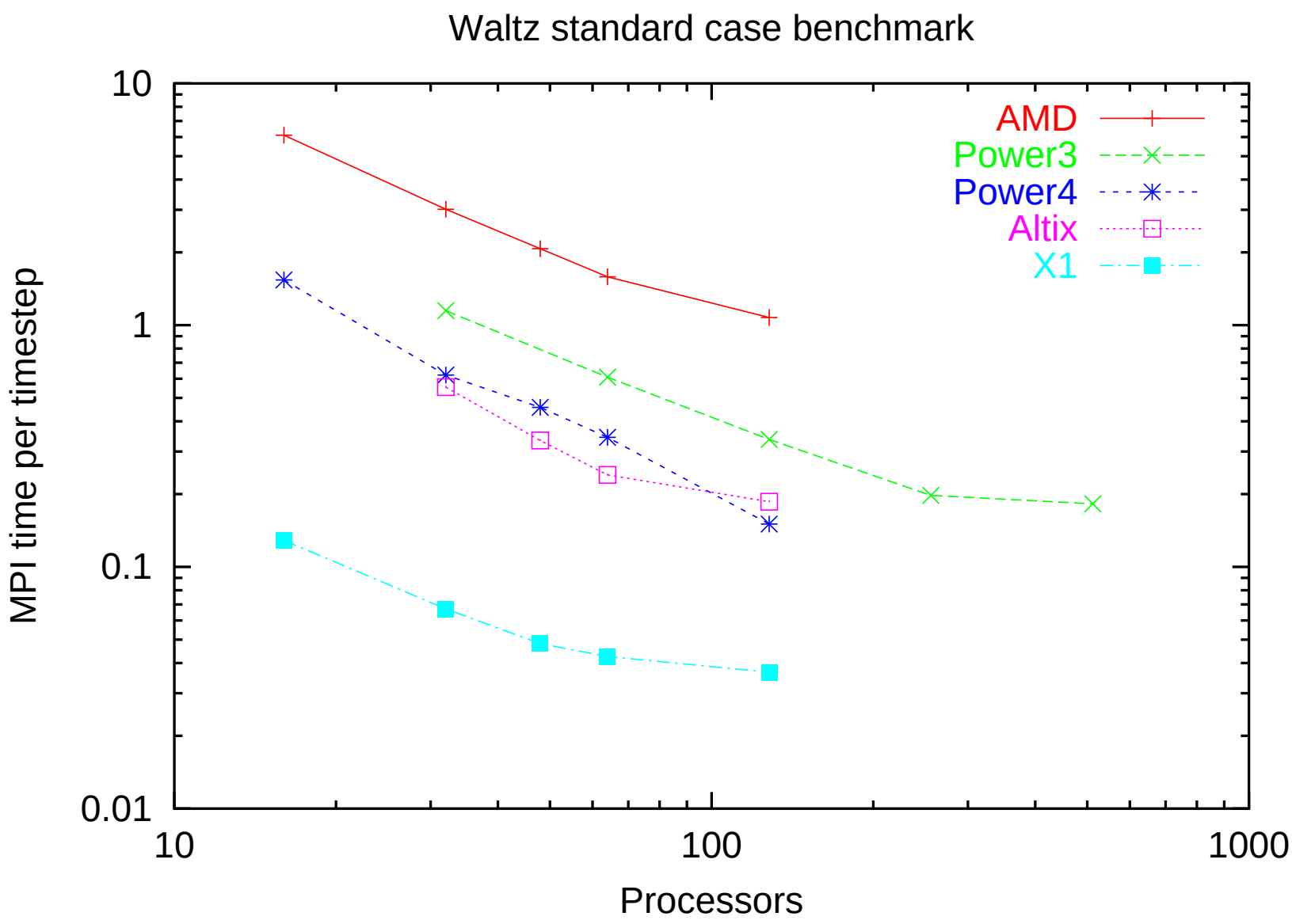
- **Resolving the local limit of global GK simulations:**
  - an existing transport scaling study [6] overestimated the *Cyclone base case* [5] benchmark value
    - contradicts the *local hypothesis* which states that global and flux-tube simulations should agree at sufficiently small ρ_*
  - GYRO found an ion diffusivity χ_i that closely agrees with the Cyclone value at small ρ_* [3] and there is a very long transient period for which χ_i exceeds the statistical average
  - Ran simulations **twice as long** as the controversial case (900 a/c_s versus 400 a/c_s) giving a true statistical turbulent steady state
- **Particle and impurity transport:**
  - **first systematic gyrokinetic study of particle transport, including impurity transport and isotope effects**
  - found that in a burning D-T plasma, the tritium is better confined than deuterium, with the implication that the D-T fuel will separate as tritium is retained
  - this trend is independent of temperature gradient and electron collision frequency

GYRO performance - Waltz standard case

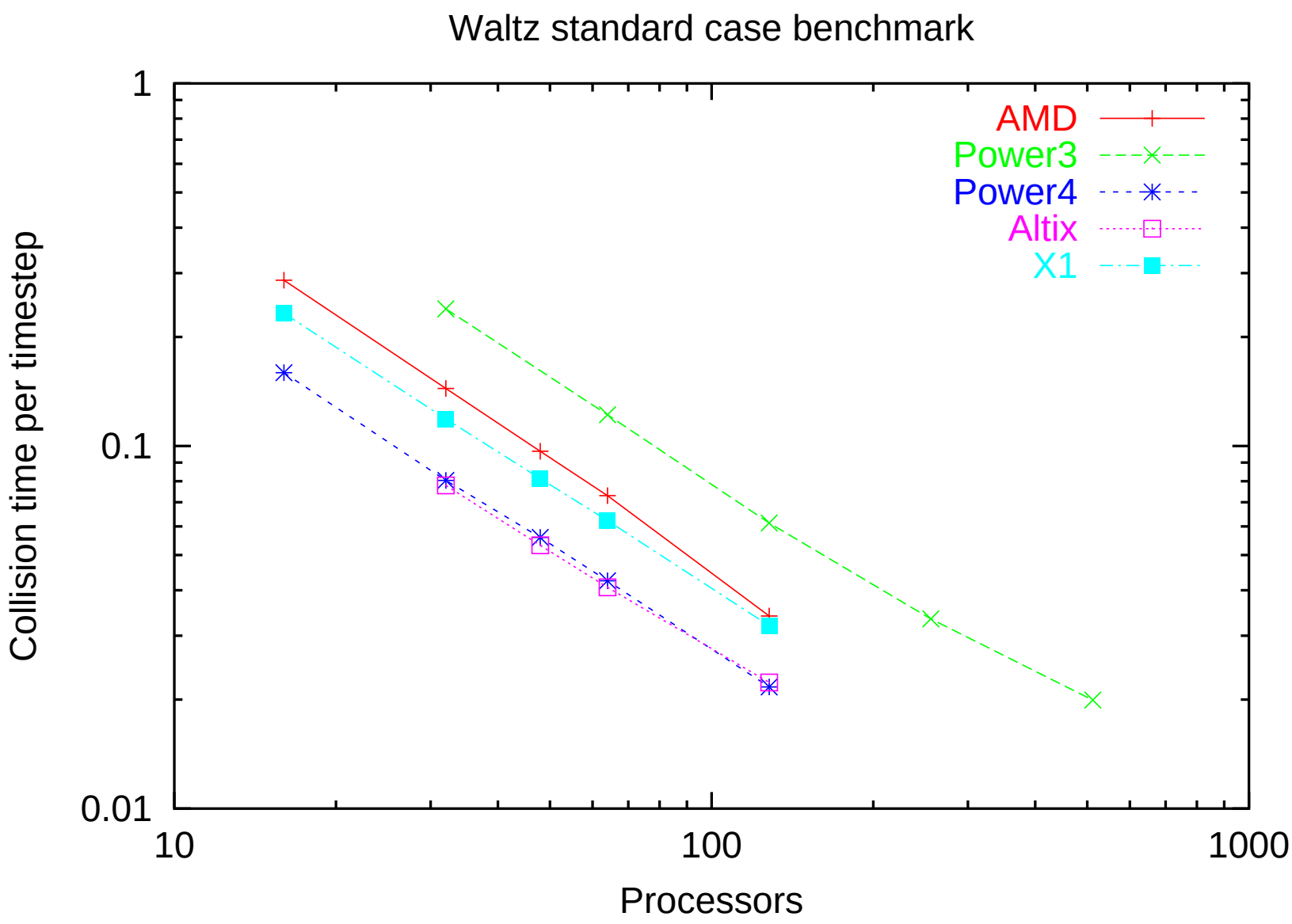
- Waltz Standard Case defined in [2]
- 500 timesteps with kinetic electrons and electron collisions
- no electromagnetic effects
- a flux-tube, 16-toroidal-mode electrostatic (electrons and ions) case on a 16x140x8x8x20x2 grid
- grid is typical of production runs and represents roughly the minimum grid size to obtain physically accurate results
  $\rightarrow$ thus it is relatively small


Waltz standard case benchmark
Seconds per timestep
Processors
100
10
1
0.1
10
100
1000
AMD
Power3
Power4
Altix
X1

Time/step



MPI Time/step



collision time/step

Advancing Science

1. *What new methods and capabilities are needed to advance the nation's scientific agenda?*

   Refinements in numerical techniques for nonstandard equations (nonlocal operators, high dimensionality). "toolkits" are not the answer.

   A critical issue for cutting-edge code development and challenging physics parameter studies is fast turn-around of small-to-medium jobs. This requires immediate access to capacity computing to supplement slower access to higher-performance capability systems.

2. *How can we coordinate our efforts to better focus on DOE's mission?*

   Exchange information like overcoming failures in software design and algorithm implementation; managing large, complex software projects; and sharing expertise on GK algorithms

Conclusions

- GYRO development has reached all its original capability objectives
- Refinements are continually being added
- Several important research results have been obtained just over the last year and a half due to greater per-processor capability
  $\rightarrow$ capability computing enabling science
- The performance of GYRO on nonvector machines is constrained by communication bandwidth, not true on X1 - the GYRO MPI_ALL_TO_ALL costs have dropped to the lowest levels ever
- Collisions perform rather poorly on the X1 despite several optimizations to improve vectorization to its current state. Any further improvement will probably be gained via a new algorithm.

References

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[4] J. Candy, R.E. Waltz, and M.N. Rosenbluth. Smoothness of turbulent transport across a minimum-q surface. *Phys. Plasmas*, 11:1879, 2004.

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