HPC Simulations of Microturbulence in Fusion Plasmas

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With contributions from:

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International Supercomputing Conference 2010

What and what for

Controlled fusion has the potential to give a major contribution to the energy production of the future.

Net gain from fusion devices needs a sufficiently large energy confinement time, i.e. the ratio between the total energy stored in the plasma and the power flowing out via conduction and convection.

Extensive computer codes have to be used for realistically simulating the complex transport dynamics driven by (micro)turbulence in plasmas.

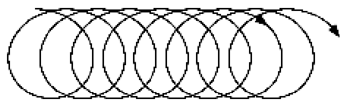
Multi-scale problems in space and time

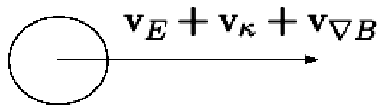
MICROTURBULENCE | **MHD EVOLUTION** | **TRANSPORT**

fluid transport

extended MHD

gyrokinetic





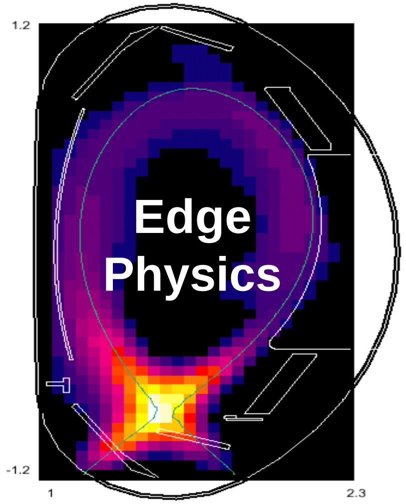
Alfvén transit time	sound transit time	MHD evolution time	transport time	resistive time

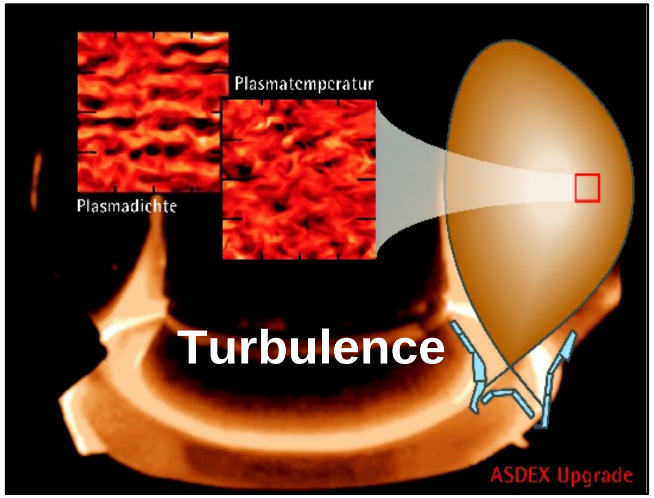
$t_A \ll t_s \ll t_{evol} \ll t_{trans} \ll t_{res}$

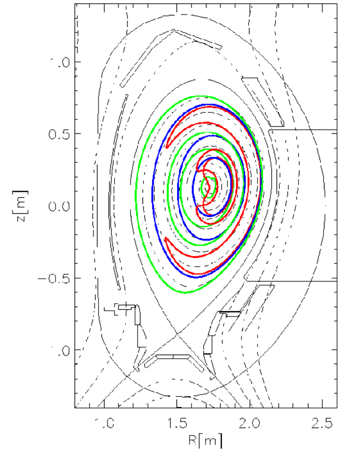
10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1}

problem time (s)

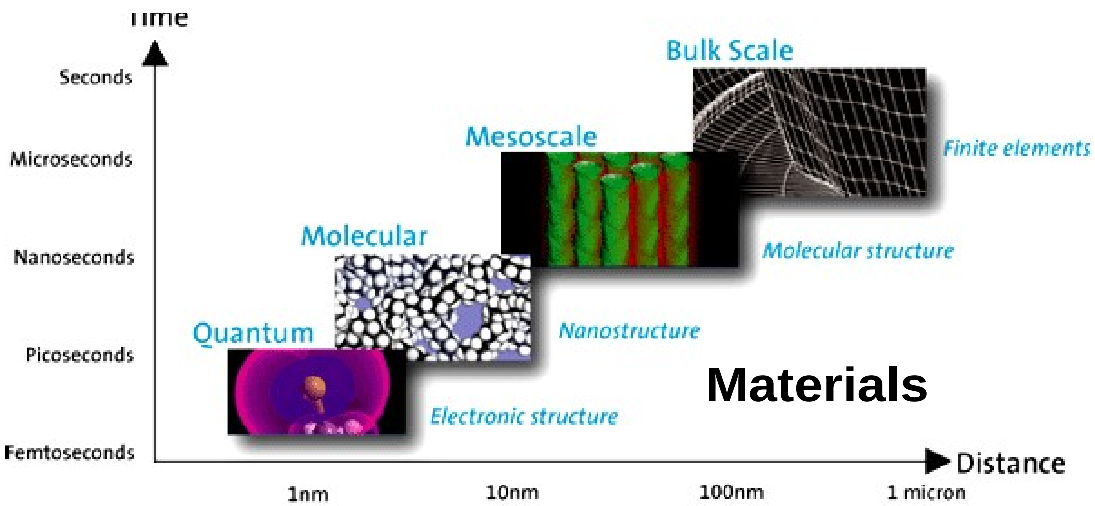
High-performance computing in fusion needed for …

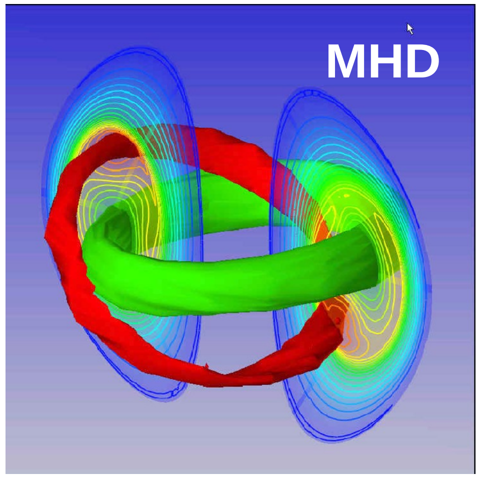






Fast Particles





Numerical Algorithms

Three classes of numerical methods

- Eulerian
  - Fixed grid in 5-dim phase space
  - Finite difference discretization of differential operators
- Semi-Lagrangian
  - Fixed grid in 5-dim phase space
  - Trace characteristics back in time to evolve distribution function
- Lagrangian: Particle-in-Cell (PIC), i.e. Monte Carlo method
  - Follow particle trajectories in 5-dim phase space
  - Project particles to real space to compute density and current

All three methods need a Poisson and parallel Ampére field solver

- Discretization with e.g. finite differences, finite elements, FFT

Numerical Algorithms

- Gyrofluid vs. gyrokinetic model
  - Choice of the most realistic physical model
- Local approximation vs. global model
  - Covering just a local “flux-tube” or the whole physical domain
- Adiabatic vs. kinetic electrons
  - Taking the full kinetics of all species into account
- Electrostatic vs. electromagnetic model
  - Taking self generated currents and Ampére’s law into account
- Collisonless vs. collisional plasma
  - Taking all values of collisionality into account

So far none of the codes covers all physical aspects!

Numerical Algorithms

- The number of relevant self-consistent (non-linear) gyrokinetic codes worldwide is between 10 and 15.
- The development of the relevant codes took typically many man-years (>5 years) and is still not finished.
- The codes are usually developed by more than one person.
- The codes run on massively parallel computers.
- The limited physical models still result from a lack of computational resources.

More powerful computers with efficient code implementations are needed!

Distributed European Infrastructure for Supercomputing Applications

Joint Research Activities in Plasma Physics + eDEISA (2004-2009)

Application enabling and support for important codes of the European plasma physics community.

DEISA Extreme Computing Initiative

The DEISA Extreme Computing Initiative (DECI) is a scheme through which European computational scientists can apply for single-project access to world-leading computational resources in the European HPC infrastructure, operated by DEISA.

> 10 million hours of computer resources for fusion under DEISA

The EFDA HPC project

HPC-FF

- 1080 nodes @ 8 cores, peak performance 101 TFlop/s
- Start of production: August 2009

- numerical algorithms
- efficient parallelization strategies
- visualization
- education

core team (5 persons)

IPP rzg RECHENZENTRUM GARCHING

+ 4 ppy in other Associations

HPC-FF at JSC

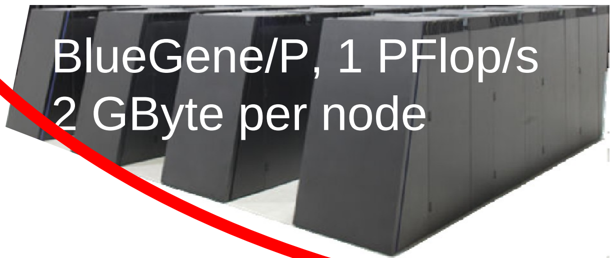
Jülich's General Purpose Supercomputer

- 2208 nodes @ 8 cores
- 24 GB per node
- Intel Nehalem-EP
- Network: Infiniband QDR
- Peak Performance 207 TFlop/s

Supercomputer for
Fusion Science HPC-FF

- 1080 nodes @ 8 cores
  of same architecture
- Peak Performance 101 TFlop/s

Flexible swapping of resources



Storage
Environment

High Level Support Team

Main tasks for HLST

The HLST team is a support unit to ensure optimal exploitation of HPC-FF, i.e. it is not focused on its own academic research.

Support for code development

- Single processor performance optimization
- Parallelization & optimization of codes for massively parallel computers
- Improvement of the parallel scalability of existing codes already ported to parallel platforms
- Implementation of algorithms and mathematical library routines to improve the efficiency of codes
- Visualization of large data sets

Relevant European Codes

- ELMFIRE
  - TKK – Aalto University School of Science and Technology
  - VTT – Technical Research Centre of Finland
- GEMR
  - Max-Planck-Institut für Plasmaphysik (IPP)
- GENE
  - Max-Planck-Institut für Plasmaphysik (IPP)
  - Centre de Recherches en Physique des Plasmas (CRPP)
- GYSELA
  - Commissariat à l'énergie atomique (CEA) – Centre de Cadarache
- ORB5
  - Centre de Recherches en Physique des Plasmas (CRPP)
  - Max-Planck-Institut für Plasmaphysik (IPP)

This list is not exhaustive!

ELMFIRE

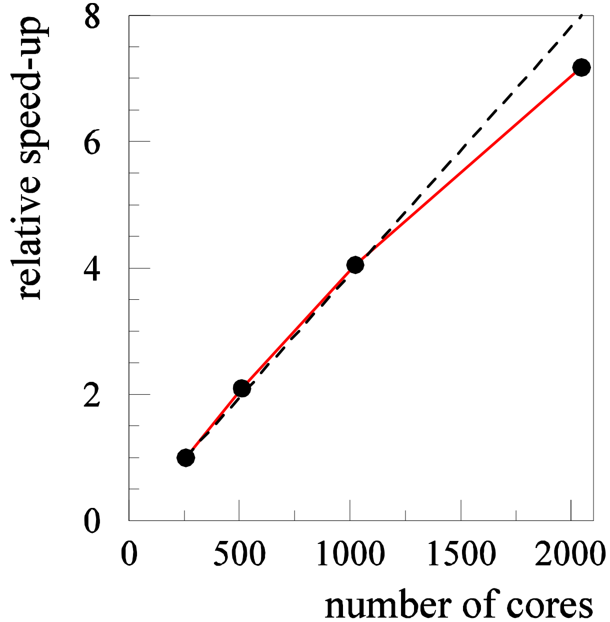
- Guiding-center orbit following gyrokinetic PIC method
- The global tokamak geometry is covered
- Electrostatic model
- Electrons and ions treated kinetically
- Momentum and energy conserving binary collisions included

Strong scaling of ELMFIRE code for the Cyclone base case
Numerical parameters:

- N=900,000,000 particles are used to sample the 5-dim phase space
- A grid of $N_s=8$, $N_\theta=150$, $N_\varphi=91$ discretizes the potential equation

ELMFIRE

Strong scaling



The job was executed on the Cray XT5 machine with AMD Opteron Barcelona Quad-Core processors and 2.3 GHz clock rate at CSC.

data contributed by S. Janhunen, TKK

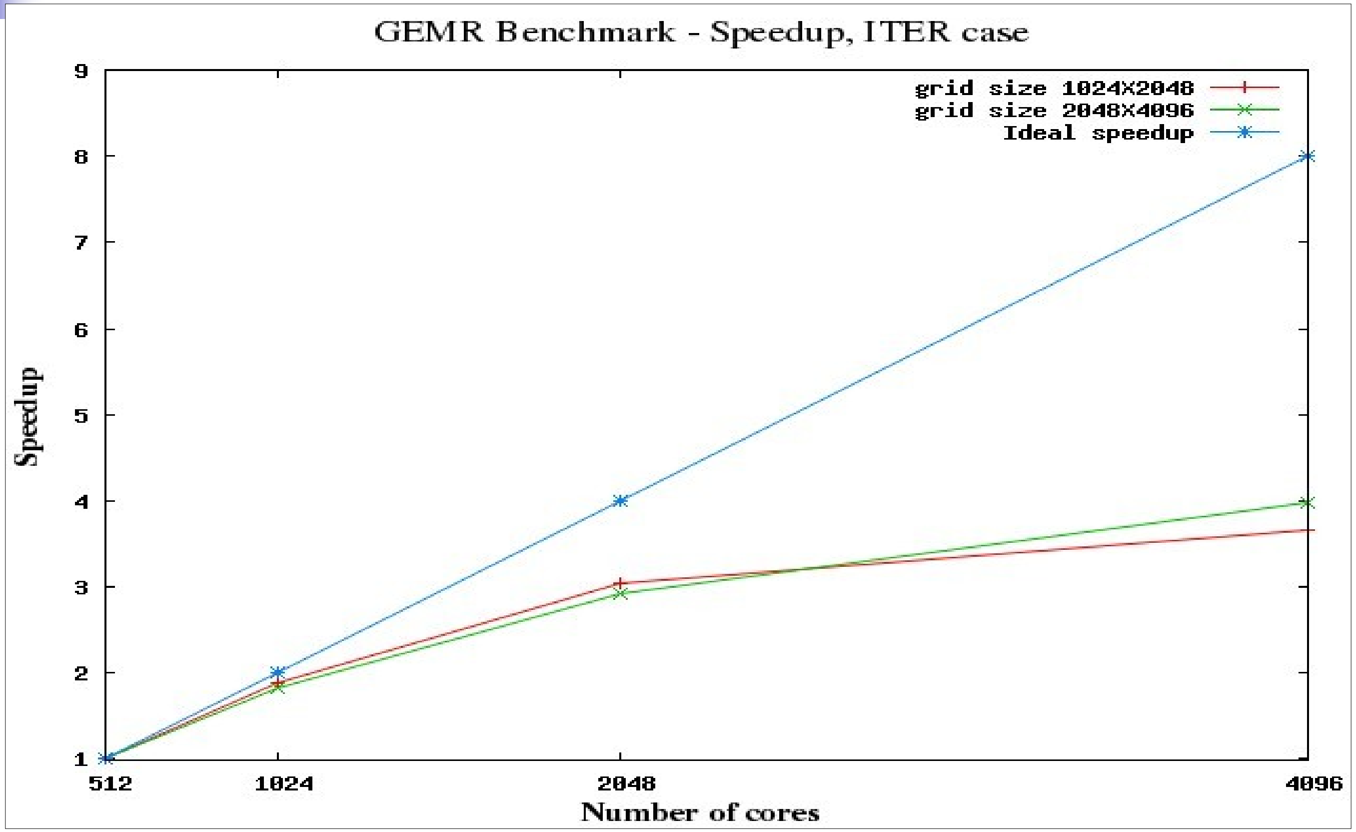
GEMR

- Gyrofluid model
- The global tokamak geometry is covered
- Electromagnetic model
- Electrons and one or more ion species
- Momentum and energy conserving binary collisions included

Strong scaling of GEMR code:

- With a grid of $N_x=1024$, $N_y=2048$, $N_s=32$
- With a grid of $N_x=2048$, $N_y=4096$, $N_s=32$

GEMR



The job was executed on the Bull HPC-FF machine with Intel Xeon X5570 Quad-Core processors and 2.93 GHz clock rate at JSC.

figure contributed by N. Hariharan and B.D. Scott, IPP

GENE

- Gyrokinetic Eulerian method
- Local “flux-tube” or global code version
- Electromagnetic model
- Electrons and one or more ion species treated kinetically
- Momentum and energy conserving binary collisions included

Strong scaling of GENE code:

Multiscale parameters:

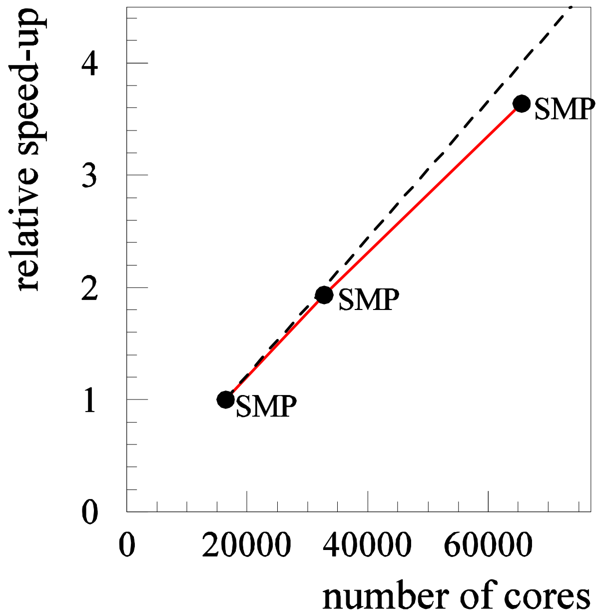
- 5-dim grid of $N_{X0}=1024$, $N_{ky}=512$, $N_{z0}=24$, $N_{v0}=96$, $N_{w0}=64$
  problem size of ≈20 TByte

Stellarator parameters:

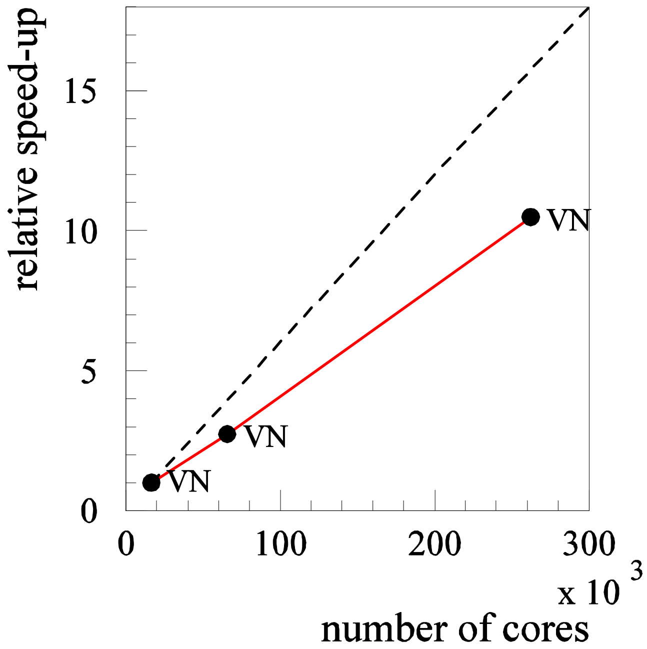
- 5-dim grid of $N_{X0}=128$, $N_{ky}=64$, $N_{z0}=512$, $N_{v0}=64$, $N_{w0}=16$
  relatively small problem size of ≈2 TByte

GENE

Strong scaling for multiscale parameters



Strong scaling for stellarator parameters



The job was executed on the IBM BlueGene/P machine with PowerPC 450 quad-core processors (SMP/VN mode) and 850 MHz clock rate at JSC.

data contributed by T. Dannert, RZG and F. Jenko, IPP

GYSELA

- Gyrokinetic Semi-Lagrangian method
- The global tokamak geometry is covered
- Electrostatic model
- Kinetic ions and adiabatic electrons
- Reduced ion-ion collisions operator

Strong scaling of GYSELA code:

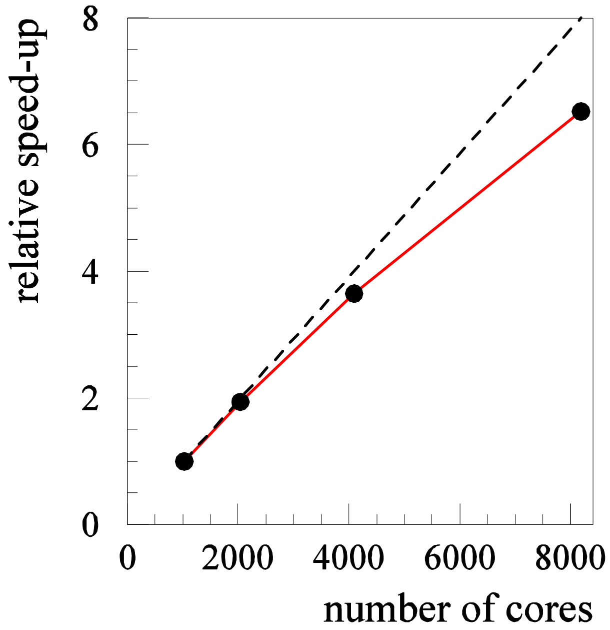
- With a grid of $N_r=512$, $N_\theta=256$, $N_\varphi=256$, $N_{vpar}=48$, $N_\mu=32$

Weak scaling of GYSELA code:

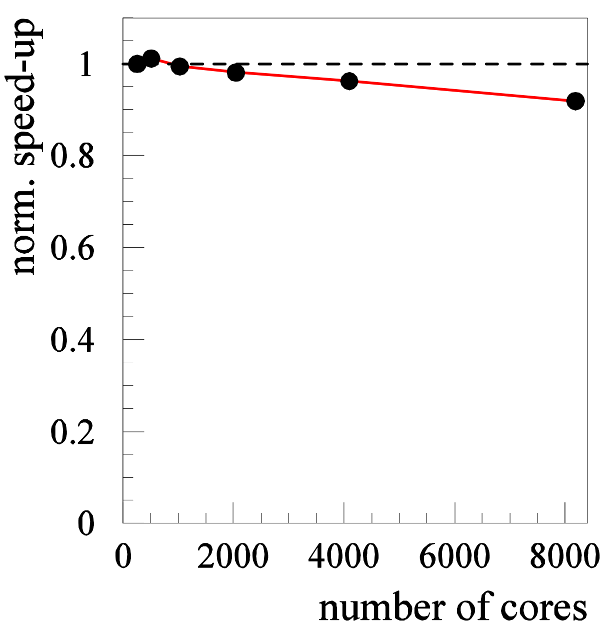
- With a grid of $N_r=512$, $N_\theta=512$, $N_\varphi=64$, $N_{vpar}=124$, $N_\mu=2,4,8,16,32,64$

GYSELA

Strong scaling



Weak Scaling



The job was executed on the SGI Altix ICE 8200 machine with Intel Xeon E5472 Quad-Core processors and 3 GHz clock rate at CINES.

data contributed by G. Latu and V. Grandgirard, CEA

ORB5

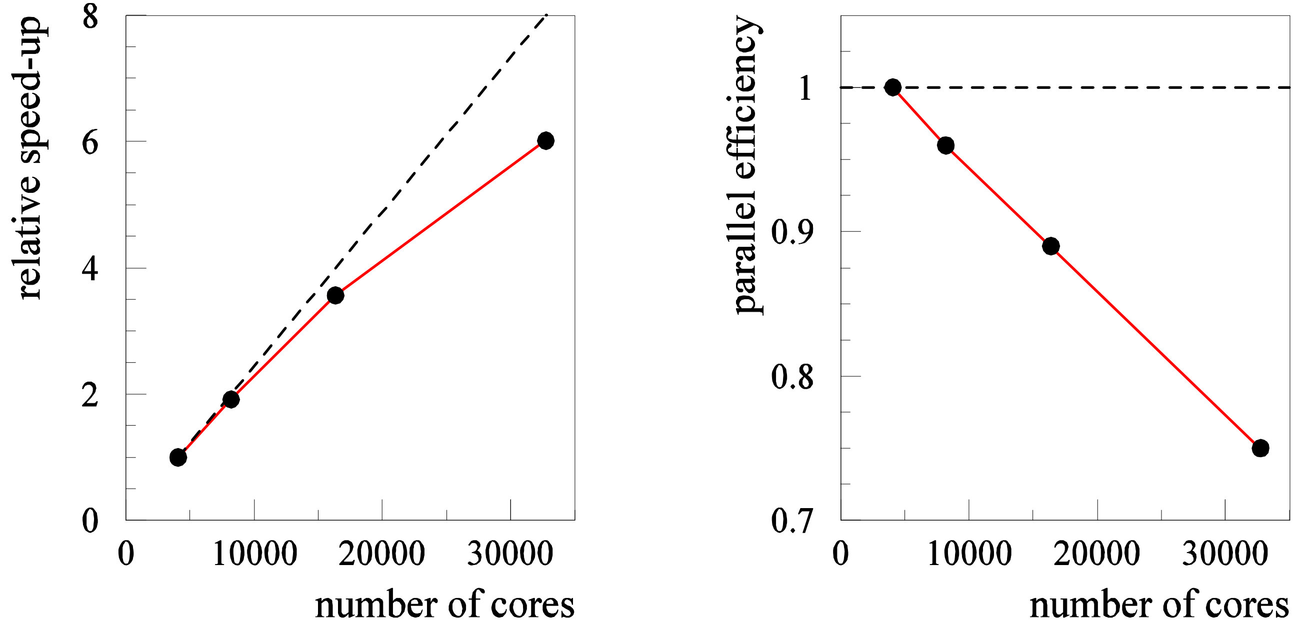
- Guiding-center orbit following gyrokinetic PIC method
- The global tokamak geometry is covered
- Electromagnetic model
- Electrons and one or more ion species treated kinetically

Strong scaling of ORB5 code for the Cyclone base case

Numerical parameters:

- N=3,145,728,000 particles are used to sample the 5-dim phase space
- A grid of N_s=128, N_θ=512, N_φ=256 discretizes the potential equation

ORB5



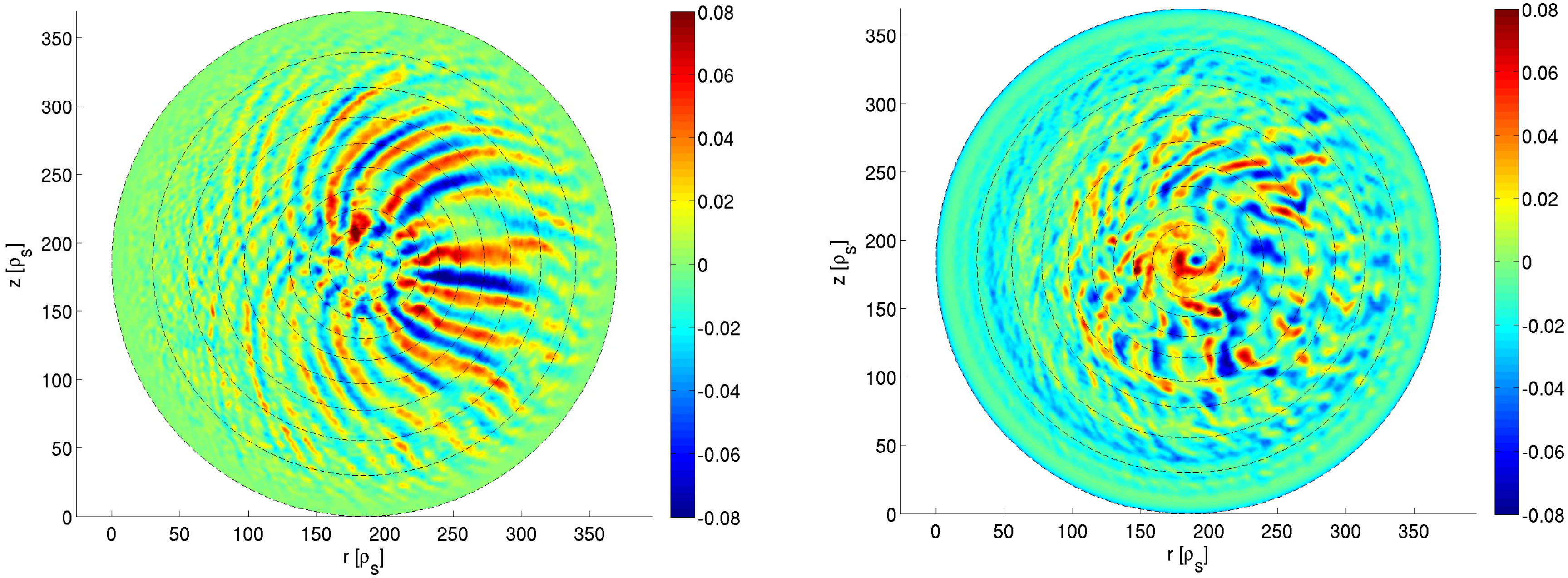
The job was executed on the IBM BlueGene/P machine with PowerPC 450 quad-core processors (VN mode) and 850 MHz clock rate at IDRIS.

data contributed by R. Tisma, RZG and A. Bottino, IPP

Zonal Flow interaction with turbulence

The zonal flow means a plasma flow along the circular contours. It arises via a self-organization phenomenon driven by plasma modes.

without zonal flow | with zonal flow

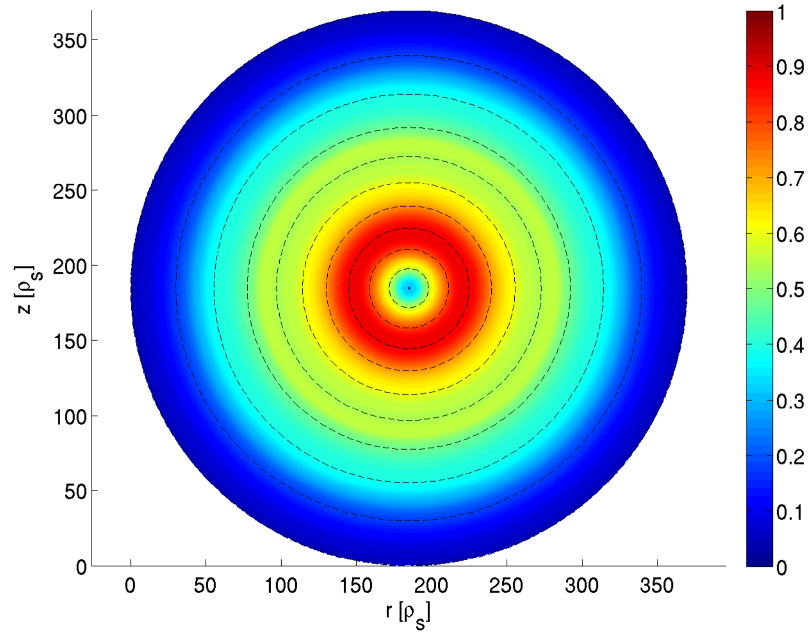


➔ The zonal flow brakes up the radial streamers (ORB5 simulation)

figures contributed by A. Bottino, IPP

Zonal Flow interaction with turbulence

The m=0, n=0 Fourier mode of the electrostatic potential drives the zonal flow via the **E** x **B** drift.

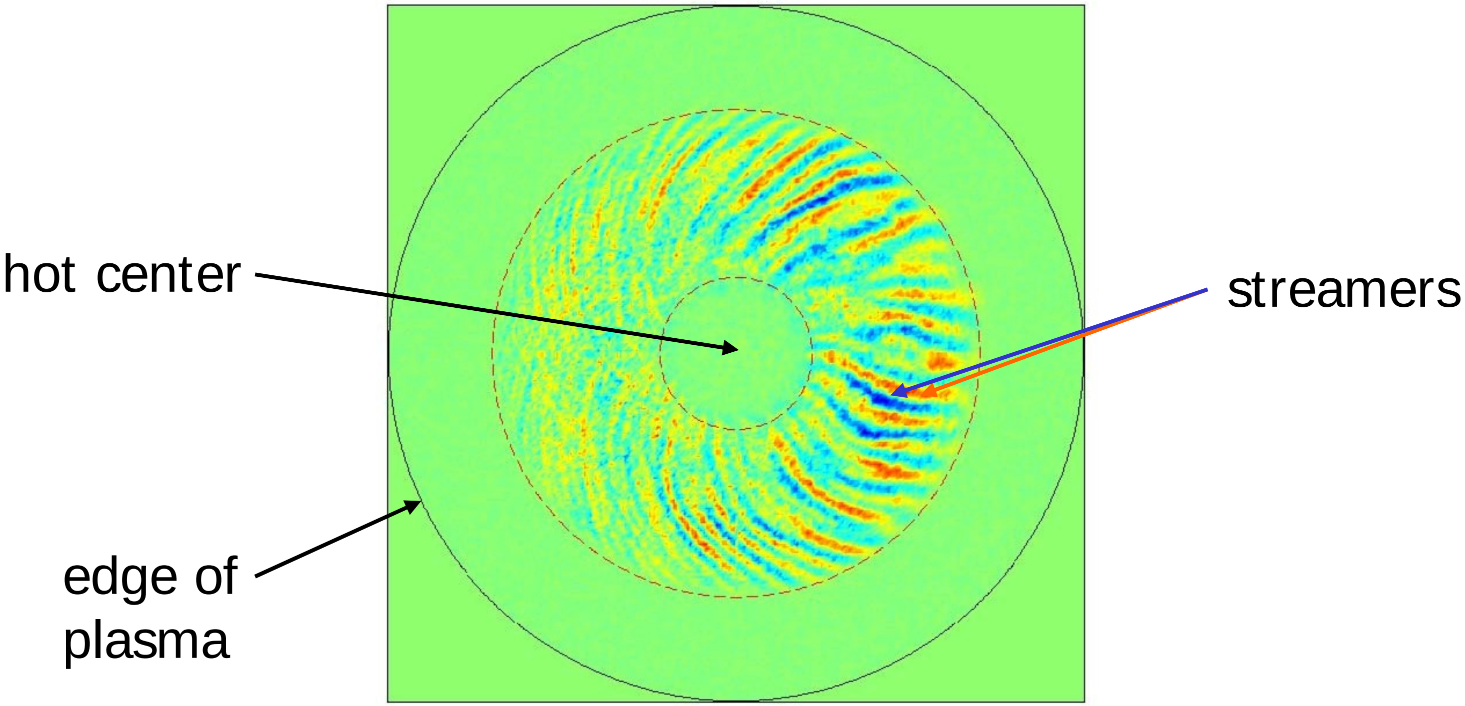


➔ The zonal flow depends on the gradient of the contours (ORB5 simulation)

figure contributed by A. Bottino, IPP

ETG driven turbulence

Electron temperature gradient (ETG) driven turbulence can contribute to heat flux due to elongated radial streamers.



A. Bottino et al., PoP **14**, Art.No: 010701, 2007 (ORB5 simulation)

Summary

- European scientists are quite active in the field of gyrokinetic turbulence simulations
- They use complementary numerical methods
- They are supported by the EFDA HPC project:
  - With a 100 TFlop/s machine (HPC-FF) for computing
  - The High Level Support Team for code optimization
- Further progress in the field will depend on algorithmic development and access to Petaflop computers
- The IFERC-CSC will provide such computational power in 2012