Fusion Simulation at Exascale and Beyond

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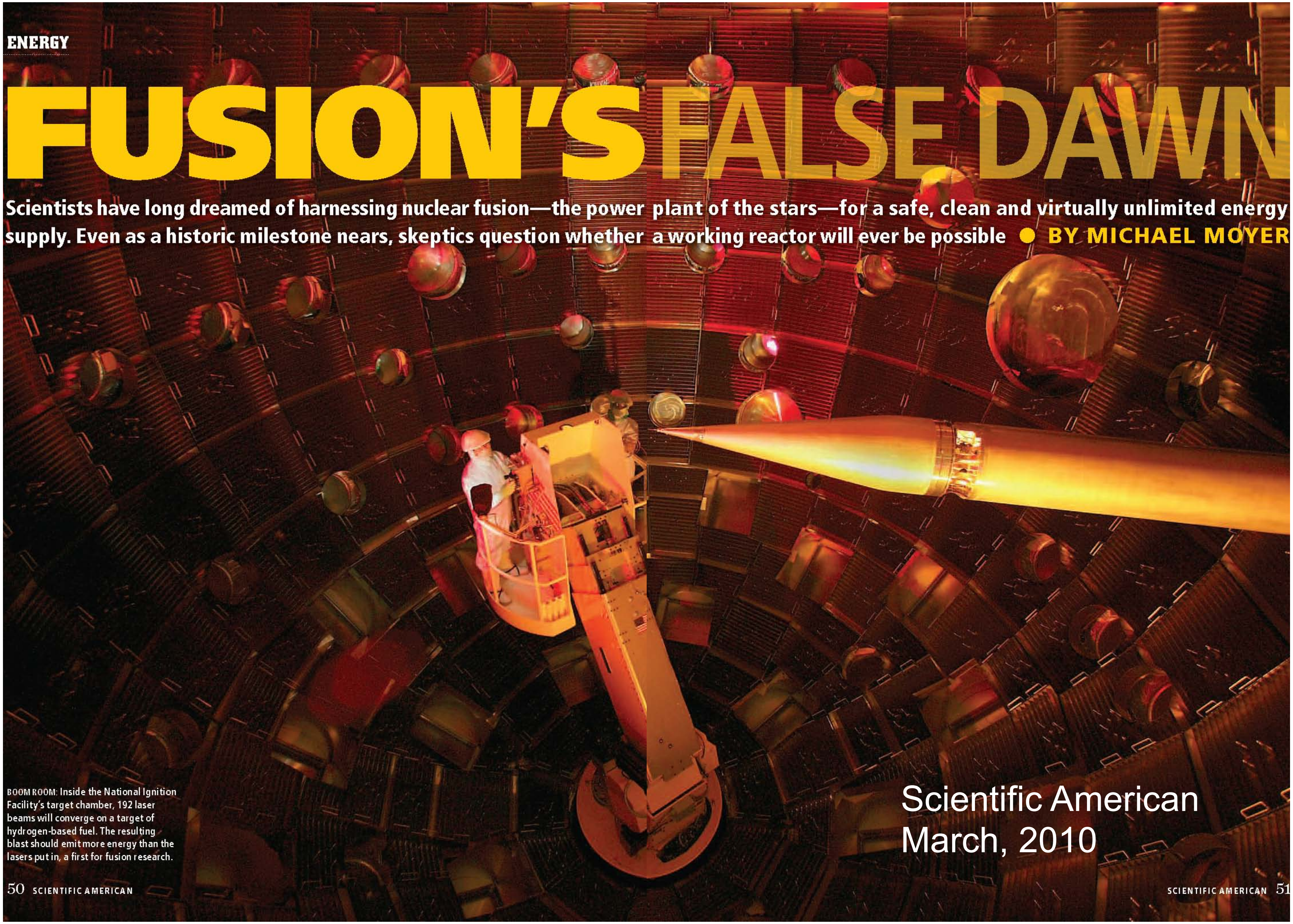
GTC Team
US DOE SciDAC ISEP Center, CAAR Project, ALCC Project
ITER-China Simulation Project
Rostoker Fellowship, TAE grant

“fusion energy is 30 years away—and always will be”



ENERGY

FUSION’S FALSE DAWN

Scientists have long dreamed of harnessing nuclear fusion—the power plant of the stars—for a safe, clean and virtually unlimited energy supply. Even as a historic milestone nears, skeptics question whether a working reactor will ever be possible ● BY MICHAEL MOYER

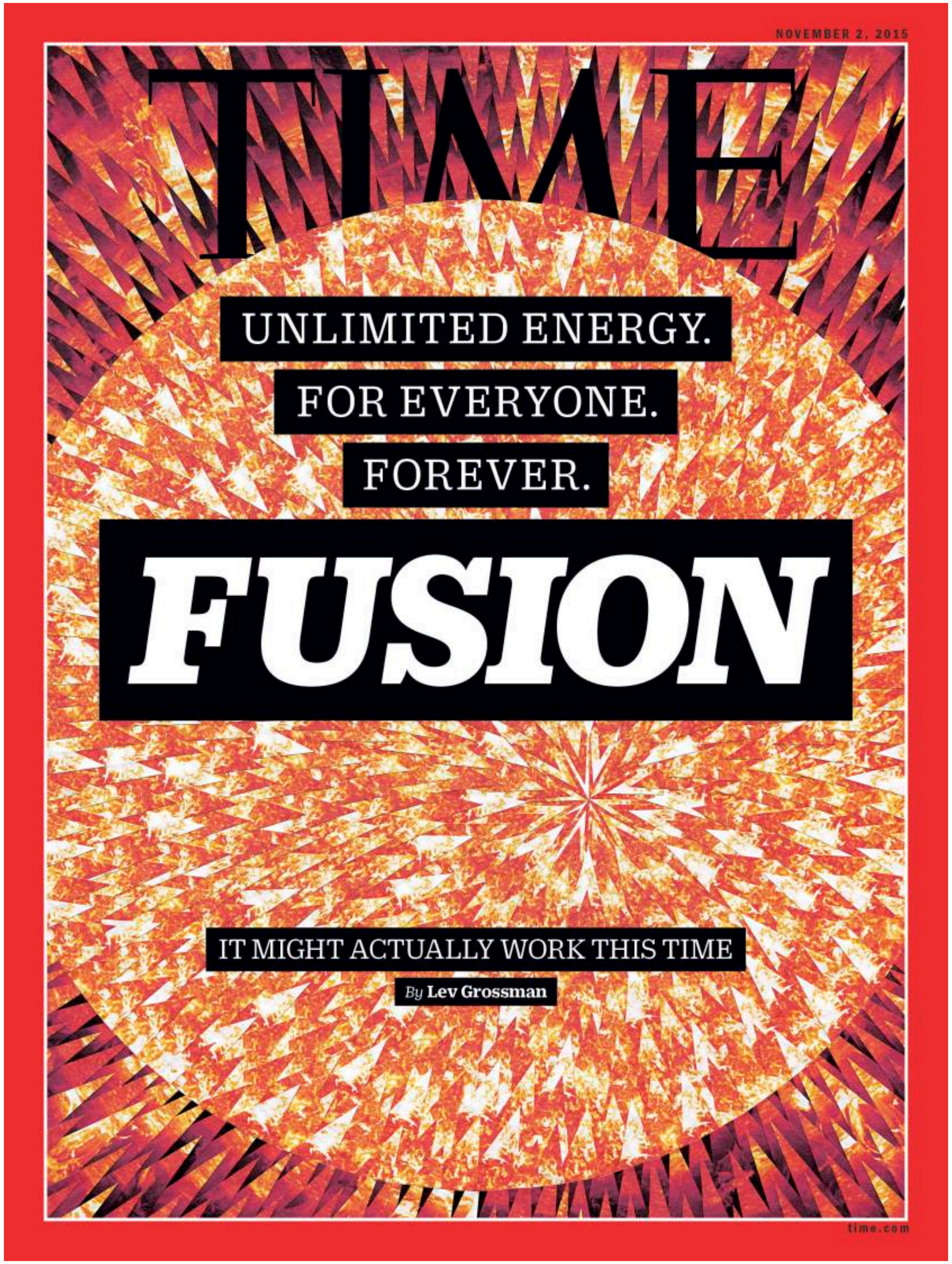
BOOM ROOM: Inside the National Ignition Facility’s target chamber, 192 laser beams will converge on a target of hydrogen-based fuel. The resulting blast should emit more energy than the lasers put in, a first for fusion research.

Scientific American
March, 2010

50 SCIENTIFIC AMERICAN

SCIENTIFIC AMERICAN 51

“IT MIGHT ACTUALLY WORK THIS TIME”



NOVEMBER 2, 2015

TIME

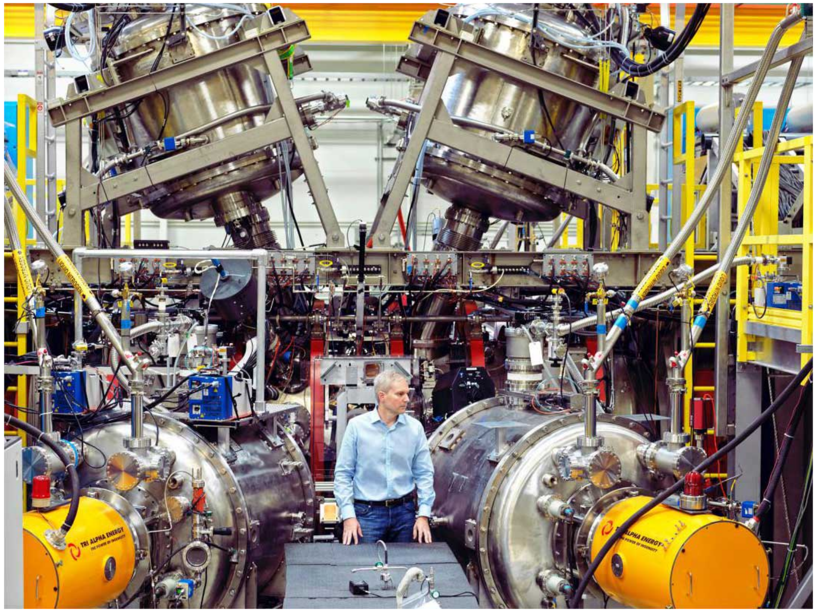
UNLIMITED ENERGY.
FOR EVERYONE.
FOREVER.

FUSION

IT MIGHT ACTUALLY WORK THIS TIME

By Lev Grossman

time.com



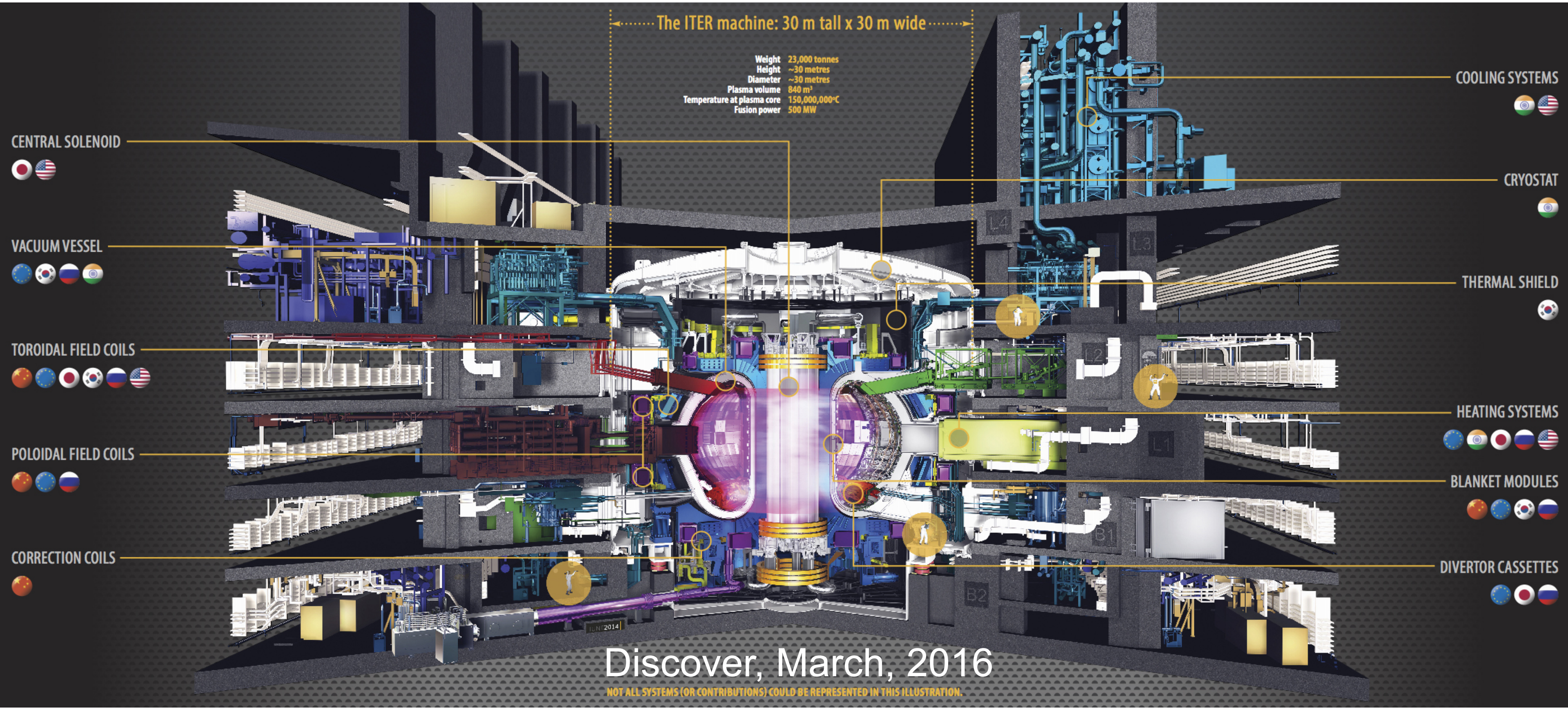
FRC fusion experiment
at TAE Technology

Norman Rostoker
Mchil Binderbauer
Toshiki Tajima

“Why Nuclear Fusion Is Always 30 Years Away?”

- How to confine fusion plasmas efficiently by magnetic fields?
  - ► Equilibrium maximizing plasma pressure
  - ► Avoiding macroscopic instability
  - ► Minimizing microturbulence transport

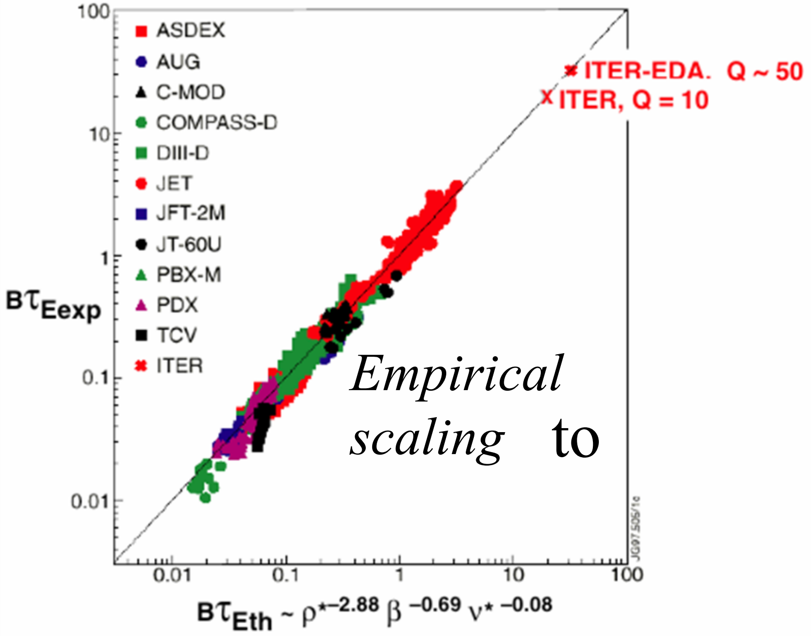
ITER ($25B): China, EU, India, Japan, Korea, Russia, USA



Discover, March, 2016

First-principles Simulation of Plasma Confinement

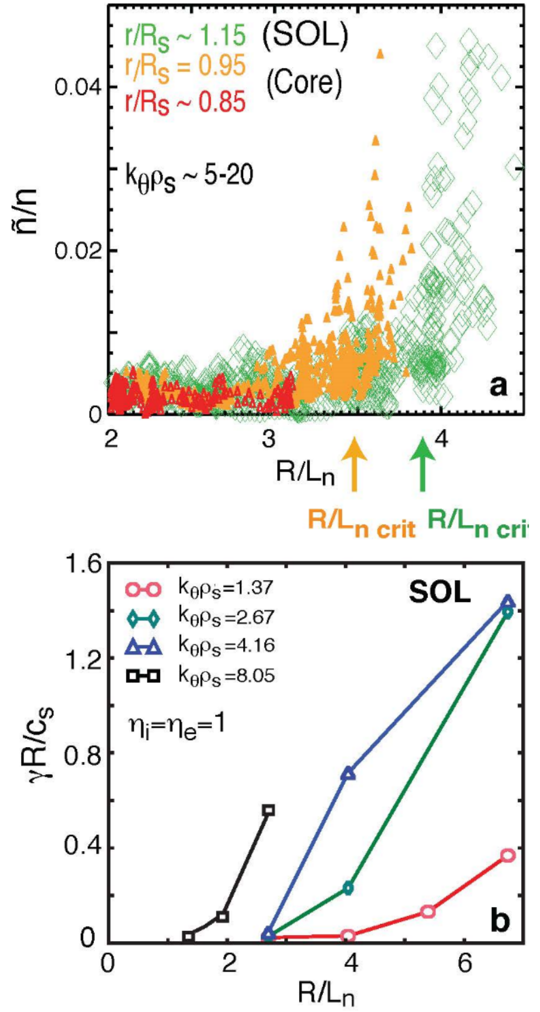
- ITER design relies on empirical scaling of confinement time τ from current tokamaks using external heating
- ITER ignition depend on balance between turbulent transport and self-heating by energetic particles (fusion products a-particles)
- Plasma confinement with self-heating by EP is one of the most uncertain issues when extrapolating from current tokamak to ITER
- First-principles simulations needed to extrapolate empirical scaling from current devices to larger ITER
- Particle-in-cell (PIC) simulation: powerful tool for studying plasmas
- PIC suffers from numerical noises
- Toshi's idea: perturbative simulation (so-called *δf* simulation method) reduce numerical noises



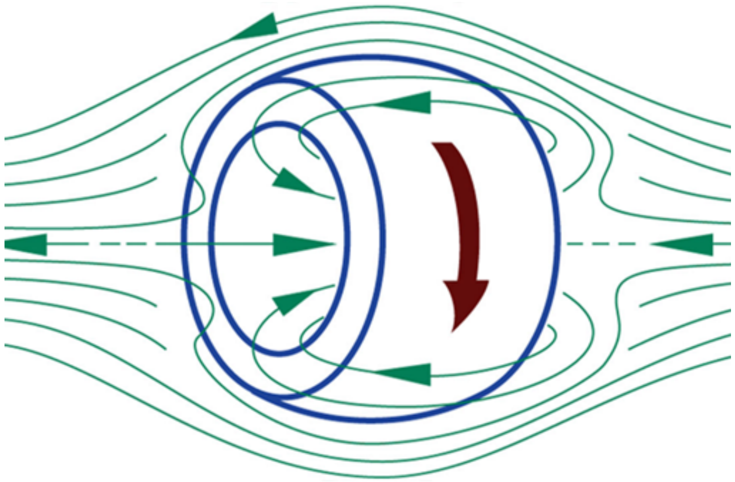
Empirical scaling to

Turbulence and Transport in FRC

- What cause heat transport in self-organized FRC?
- Microscopic driftwave is expected to be unstable due to bad curvature of magnetic field lines
- PIC code GTC [*Science, 1998*] finds ion-scale modes stable in core: a big surprise!
  - Stabilized by magnetic pressure gradient, large Larmor radius, short magnetic field lines
- SOL driftwaves unstable with critical pressure gradient, agree qualitatively with C-2 FRC data
- SOL turbulence nonlinear spreads into core
- See posters by D. Fulton, C. Lau, J. Bao, L. Schmitz



First Evidence of Suppressed Ion-scale Turbulence in a Hot High-β Plasma, L. Schmitz et al, *Nature Communications* **7**, 13860 (2016).

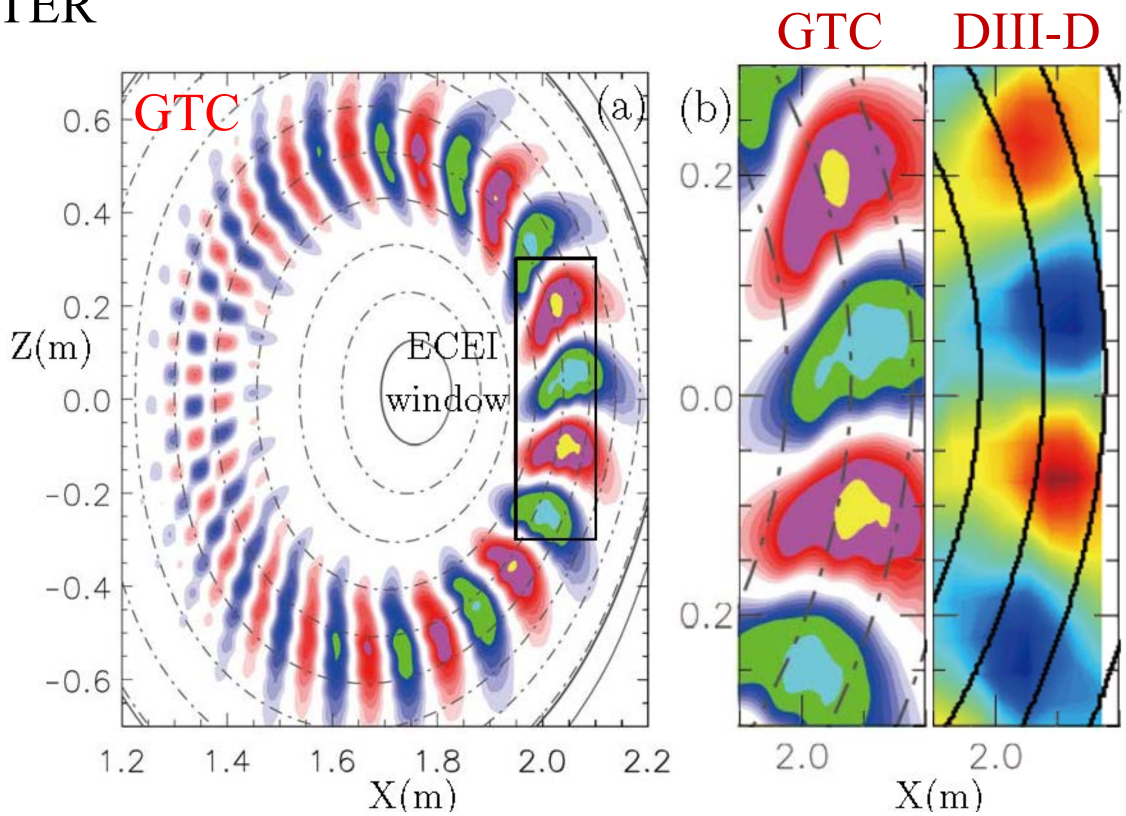


Integrated Simulation of Energetic Particles

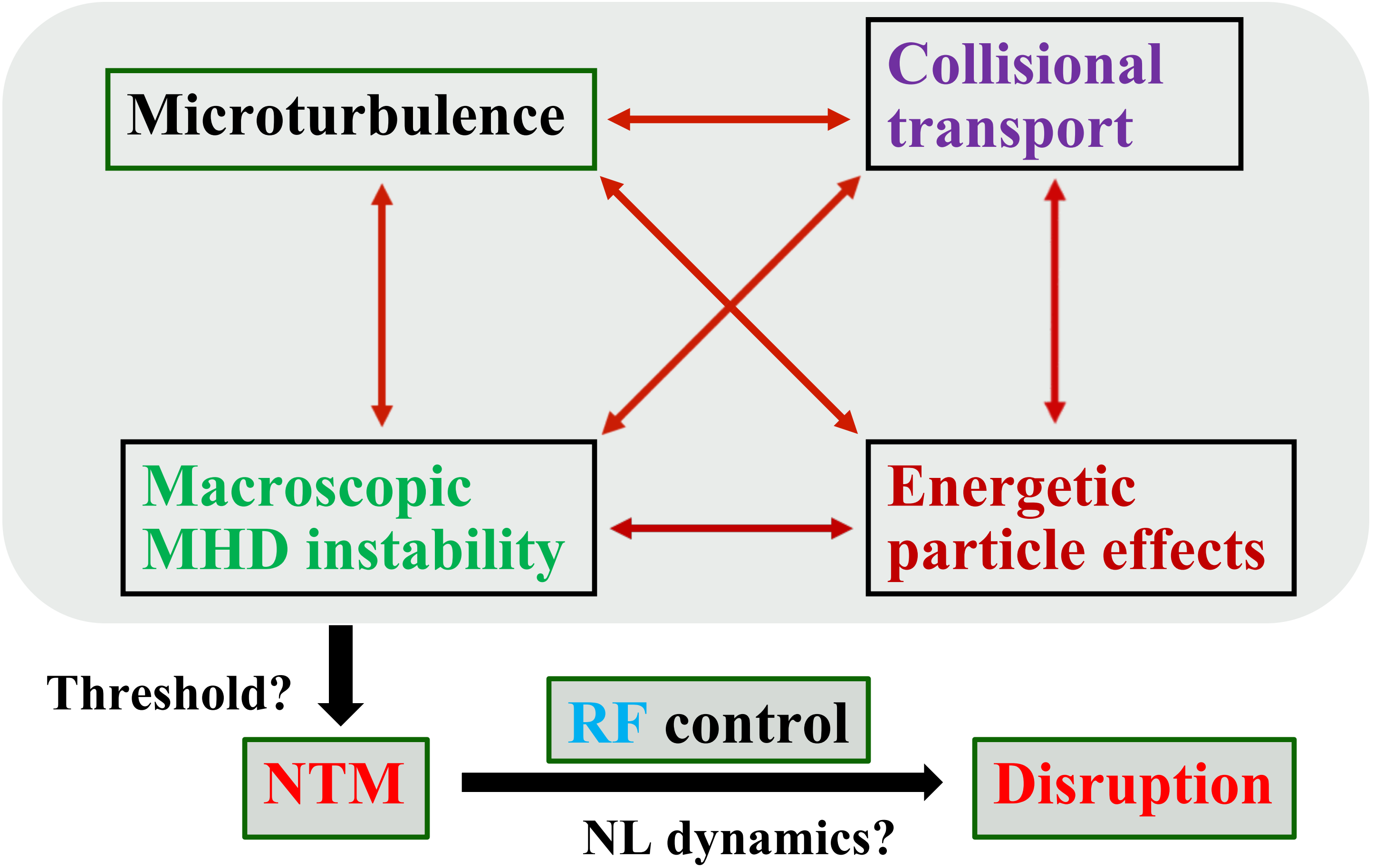
- EP excites Alfven wave instabilities, which drive EP transport
- GTC simulation of toroidal Alfven eigenmode (TAE) verified and validated in DIII-D tokamak
- Integrated simulations of EP in burning plasmas to address nonlinear interactions of multiple kinetic-MHD processes
    - ► EP confinement property in ITER
    - ► EP effects on stability and transport of thermal plasmas

TAE in DIII-D shot # 142111 at 525ms

[Z. X. Wang et al, PRL2013]



Integrated Simulation Needed to Study Nonlinear Interactions of Multiple Kinetic-MHD Processes



Microturbulence

Collisional transport

Macroscopic MHD instability

Energetic particle effects

Threshold?

NTM

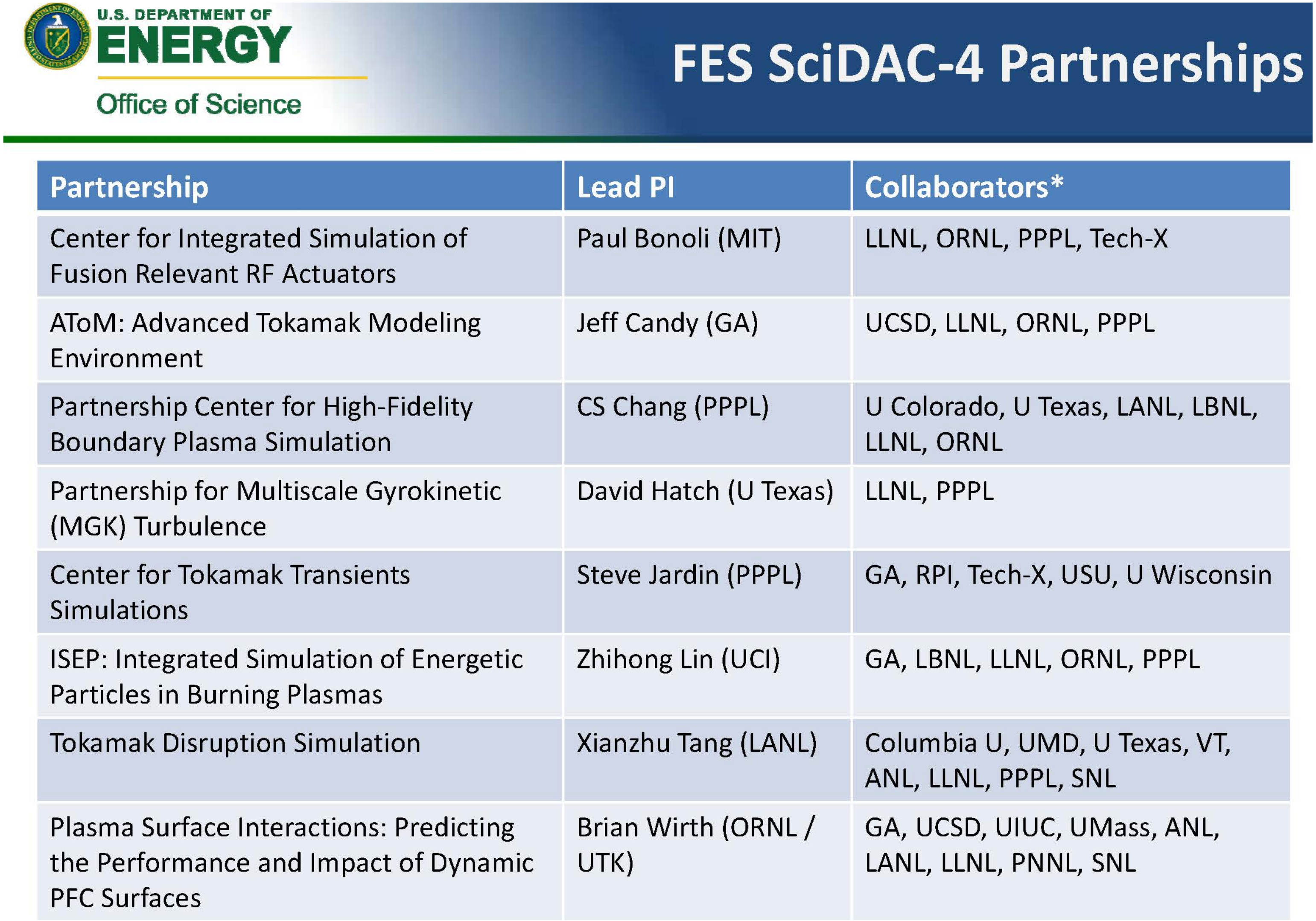
RF control

Disruption

NL dynamics?

- Neoclassical tearing mode (NTM) is the most likely instability leading to disruption.
- NTM excitation depends on nonlinear interaction of magnetohydrodynamic (MHD) instability, microturbulence, collisional (neoclassical) transport, and energetic particle (EP) effects. NTM control requires radio frequency (RF) waves.

- First-principles, integrated fusion simulation
  - ✓ ITER IMAS: Integrated Modelling and Analysis Suites
  - ✓ US SciDAC: Scientific Discovery through Advanced Computing
- Collaborations: theory, experiment, applied math, computer science



U.S. DEPARTMENT OF ENERGY

Office of Science

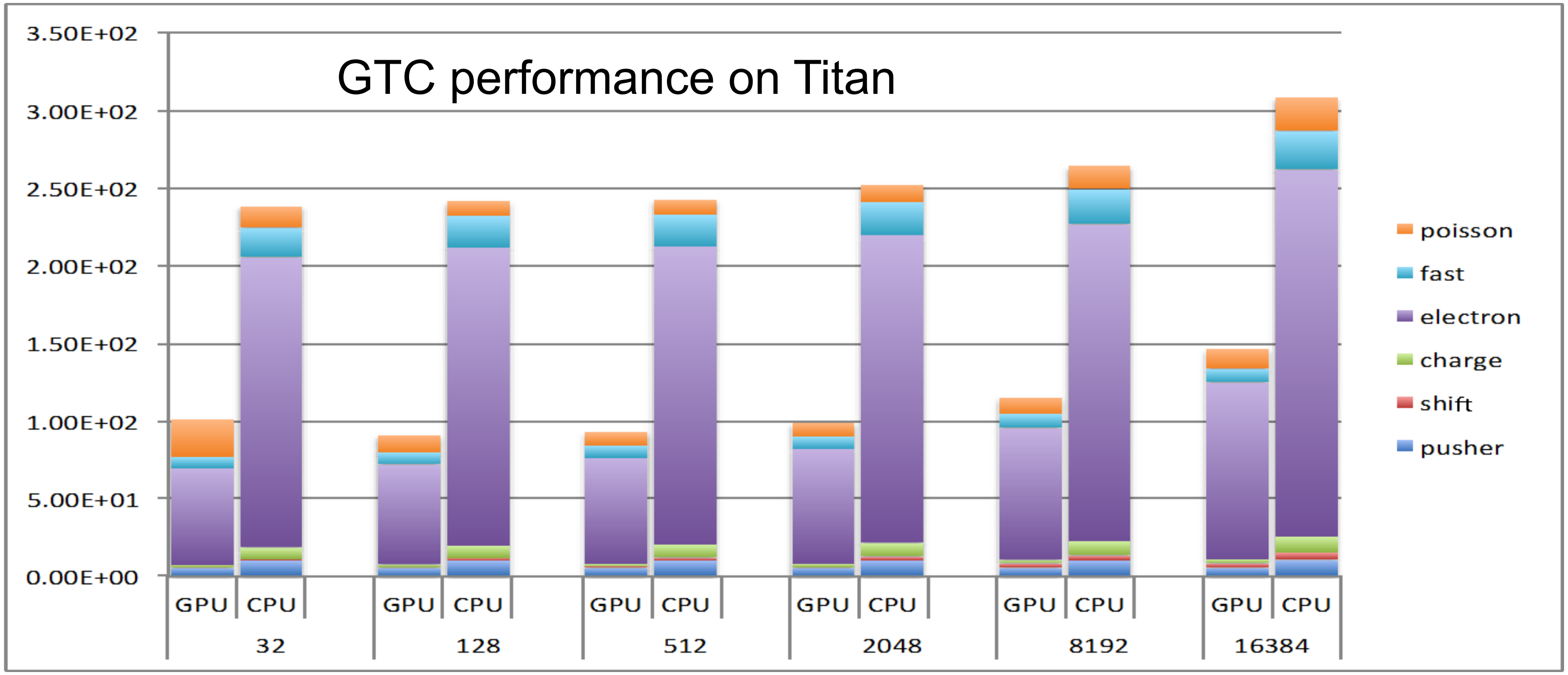
FES SciDAC-4 Partnerships

Partnership	Lead PI	Collaborators*
Center for Integrated Simulation of Fusion Relevant RF Actuators	Paul Bonoli (MIT)	LLNL, ORNL, PPPL, Tech-X
AToM: Advanced Tokamak Modeling Environment	Jeff Candy (GA)	UCSD, LLNL, ORNL, PPPL
Partnership Center for High-Fidelity Boundary Plasma Simulation	CS Chang (PPPL)	U Colorado, U Texas, LANL, LBNL, LLNL, ORNL
Partnership for Multiscale Gyrokinetic (MGK) Turbulence	David Hatch (U Texas)	LLNL, PPPL
Center for Tokamak Transients Simulations	Steve Jardin (PPPL)	GA, RPI, Tech-X, USU, U Wisconsin
ISEP: Integrated Simulation of Energetic Particles in Burning Plasmas	Zhihong Lin (UCI)	GA, LBNL, LLNL, ORNL, PPPL
Tokamak Disruption Simulation	Xianzhu Tang (LANL)	Columbia U, UMD, U Texas, VT, ANL, LLNL, PPPL, SNL
Plasma Surface Interactions: Predicting the Performance and Impact of Dynamic PFC Surfaces	Brian Wirth (ORNL / UTK)	GA, UCSD, UIUC, UMass, ANL, LANL, LLNL, PNNL, SNL

Mandrekas
DOE OFES
2017

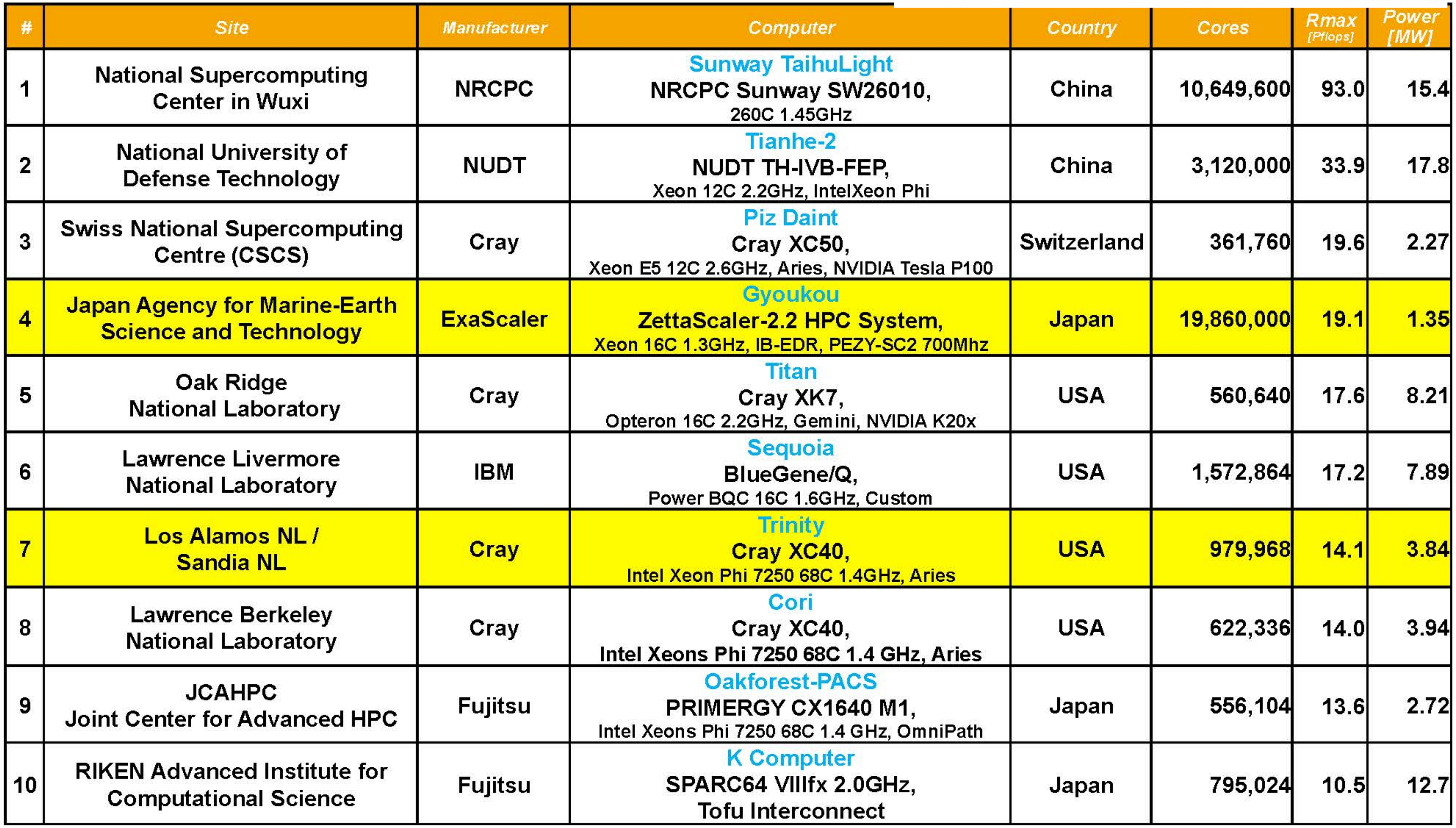
Large Scale Fusion Simulation Requires Supercomputing

- Large scale simulation requires access to and effective utilization of modern supercomputers with heterogeneous architecture
- DOE ASCR Leadership Computing Challenge (ALCC)
- GTC ALCC: UCI, PPPL, GA, ORNL



Optimizing Simulation Code for Exa Scale Computing

- GTC CAAR (Center for Accelerated Application Readiness): UCI, PU, ORNL, NVIDIA, IBM
- GTC ported to upcoming SUMMIT (200PF) & Tianhe-3 (1 EF): next talk by W. Zhang of IOP



#	Site	Manufacturer	Computer	Country	Cores	Rmax [Pflops]	Power [MW]
1	National Supercomputing Center in Wuxi	NRCPC	Sunway TaihuLight NRCPC Sunway SW26010, 260C 1.45GHz	China	10,649,600	93.0	15.4
2	National University of Defense Technology	NUDT	Tianhe-2 NUDT TH-IVB-FEP, Xeon 12C 2.2GHz, IntelXeon Phi	China	3,120,000	33.9	17.8
3	Swiss National Supercomputing Centre (CSCS)	Cray	Piz Daint Cray XC50, Xeon E5 12C 2.6GHz, Aries, NVIDIA Tesla P100	Switzerland	361,760	19.6	2.27
4	Japan Agency for Marine-Earth Science and Technology	ExaScaler	Gyoukou ZettaScaler-2.2 HPC System, Xeon 16C 1.3GHz, IB-EDR, PEZY-SC2 700Mhz	Japan	19,860,000	19.1	1.35
5	Oak Ridge National Laboratory	Cray	Titan Cray XK7, Opteron 16C 2.2GHz, Gemini, NVIDIA K20x	USA	560,640	17.6	8.21
6	Lawrence Livermore National Laboratory	IBM	Sequoia BlueGene/Q, Power BQC 16C 1.6GHz, Custom	USA	1,572,864	17.2	7.89
7	Los Alamos NL / Sandia NL	Cray	Trinity Cray XC40, Intel Xeon Phi 7250 68C 1.4GHz, Aries	USA	979,968	14.1	3.84
8	Lawrence Berkeley National Laboratory	Cray	Cori Cray XC40, Intel Xeons Phi 7250 68C 1.4 GHz, Aries	USA	622,336	14.0	3.94
9	JCAHPC Joint Center for Advanced HPC	Fujitsu	Oakforest-PACS PRIMERGY CX1640 M1, Intel Xeons Phi 7250 68C 1.4 GHz, OmniPath	Japan	556,104	13.6	2.72
10	RIKEN Advanced Institute for Computational Science	Fujitsu	K Computer SPARC64 VIIIfx 2.0GHz, Tofu Interconnect	Japan	795,024	10.5	12.7

Strohmaier
SC17