Multi-Node Multi-GPU Implementation of Micromagnetic Model for Spintronics Devices

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Why Multi-Node & GPUs Micromagnetics?

- Micromagnetic (μMag) simulation is useful for developing spintronics devices, such as MRAMs, spin-torque oscillators (STOs), and HDDs.
- Large-scale & high-speed μMag simulator is indispensable for elucidating physical phenomena in such spintronics devices, e.g., inter-magnet interactions in MRAM cells array, STOs array, HDDs' recording media.
- The simplest implementation of μMag model is the finite-difference method (FDM) and has been widely used[1], mainly on CPU-cluster computing system.
- GPUs have been recently used to speed up FDM-based μMag simulations, and there are several open-source and commercial GPU-used simulators[2,3,4].
- In the conventional GPU-used μMag simulators, the number of spatially discretized meshes is limited (typically a few million) because of a single GPU memory capacity (e.g., 6GB for Tesla K20X).

➡ FDM-based μMag simulation code using "MPI+CUDA" on multiple node & multiple GPU computing system

Simulation Codes

- Our simple FDM-based μMag code solves the Landau-Lifshitz-Gilbert-Slonczewski (LLGS) equation for the magnetization vector field $\boldsymbol{m}(\boldsymbol{r},t)$:

$$\frac{\partial \boldsymbol{m}(\boldsymbol{r},t)}{\partial t} = -\gamma \boldsymbol{m}(\boldsymbol{r},t) \times \boldsymbol{H}_{\mathrm{eff}}(\boldsymbol{r},t) + \alpha(\boldsymbol{r},t)\boldsymbol{m}(\boldsymbol{r},t) \times \frac{\partial \boldsymbol{m}(\boldsymbol{r},t)}{\partial t}$$

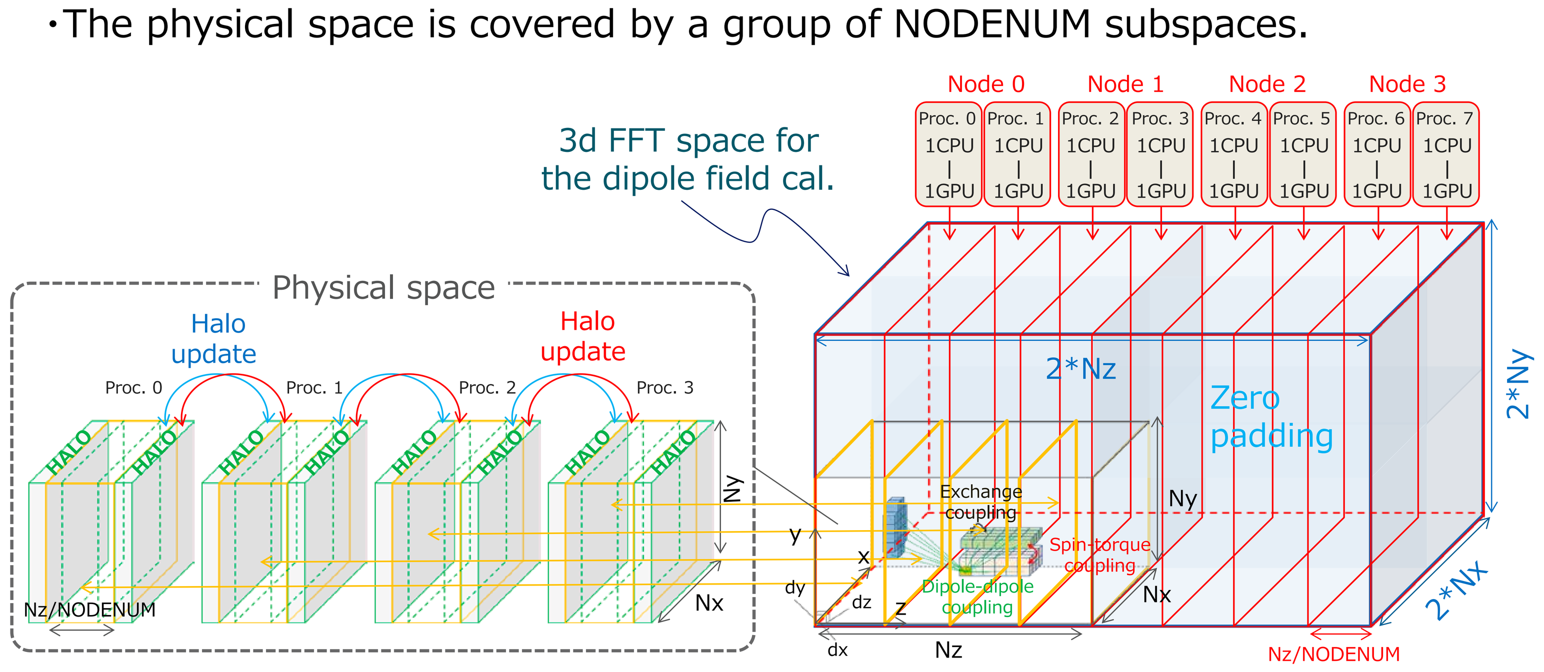
- The effective field, $\boldsymbol{H}_{\mathrm{eff}}(\boldsymbol{r},t)$, includes the external magnetic field, the dipole field, the exchange coupling, and the spin-torque coupling, etc.
- Various types of nanomagnets can be placed in a physical space.
- The physical space is discretized into Nx x Ny x Nz rectangular meshes.
- Heun's method (2nd-order Runge-Kutta method) is used for the time evolution of the LLGS equation.
- Fourier transform method is used to calculate the dipole magnetic field. The "3d-FFT space" of (2*Nx)*(2*Ny)*(2*Nz) meshes with zero padding is secured for the calculation.

Nodes & GPUs Allocation

・For a simple implementation on 2 CPUs—2 GPUs/node environment, the 3d-FFT space is partitioned in the z direction into 2*NODENUM subspaces.

・1CPU—1GPU pair controlled by an MPI process is allocated to each subspace.

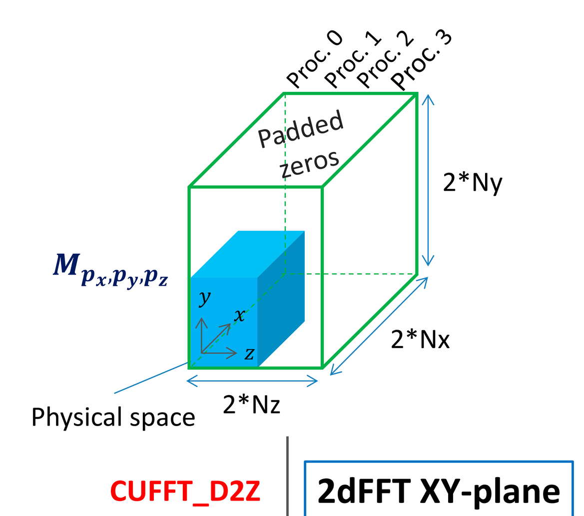
・The physical space is covered by a group of NODENUM subspaces.



[Example of hardware allocation (NODENUM=4)]

Dipole Field Calculation Using 3dFFT

2dFFT→Transpose→1dFFT → Multiplication →1dFFT→Transpose→2dFFT



Calculation Procedure of the Dipole Field $\boldsymbol{H}_{p_x,p_y,p_z}$

Forward FFT of magnetization vector (x, y, z components):

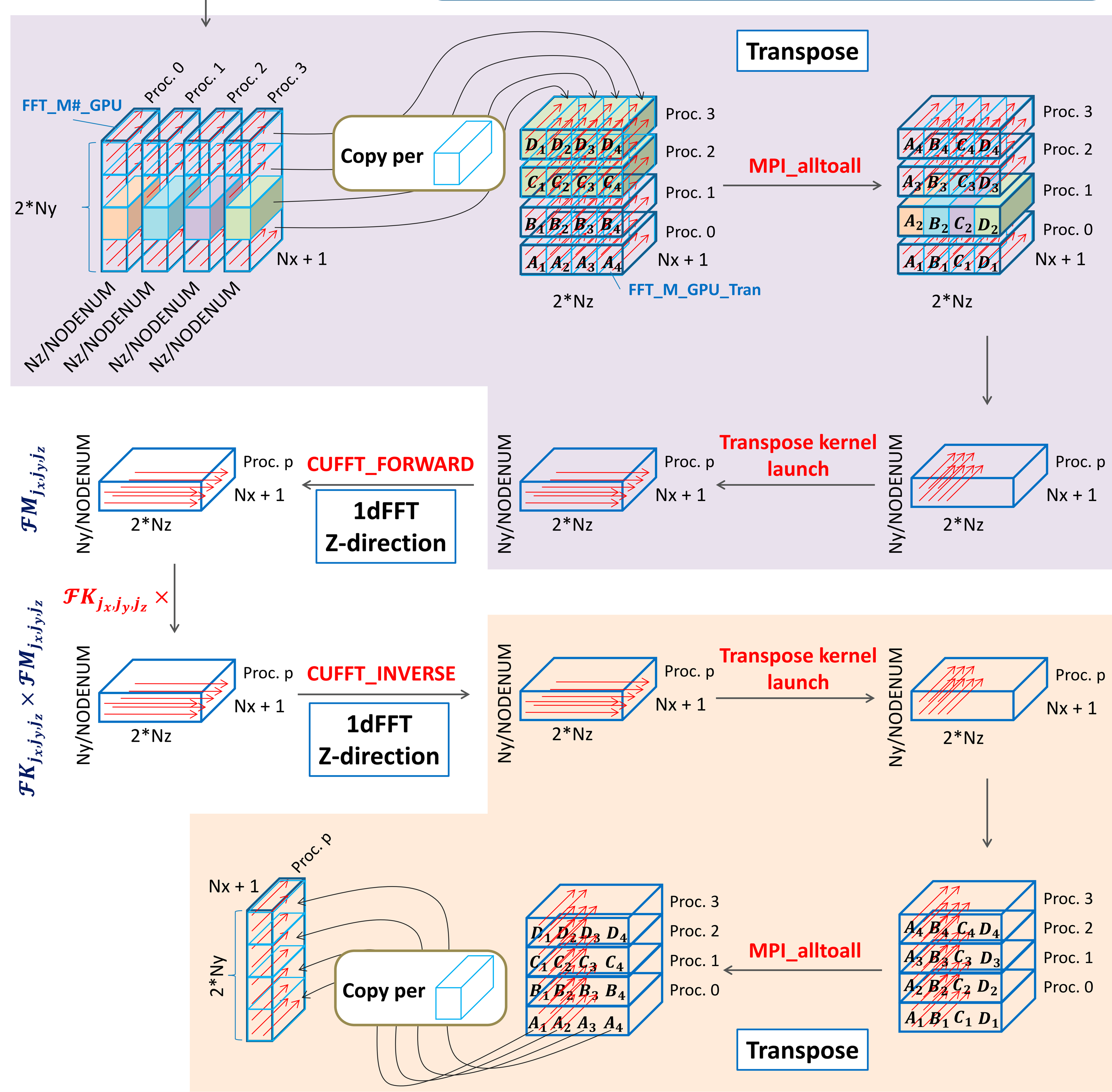
$$\mathcal{F}\boldsymbol{M}_{j_x,j_y,j_z} = \sum_{p_z=0}^{2N_z-1}\sum_{p_y=0}^{2N_y-1}\sum_{p_x=0}^{2N_x-1} \boldsymbol{M}_{p_x,p_y,p_z}\, e^{-2\pi i(j_x p_x/2N_x + j_y p_y/2N_y + j_z p_z/2N_z)}$$

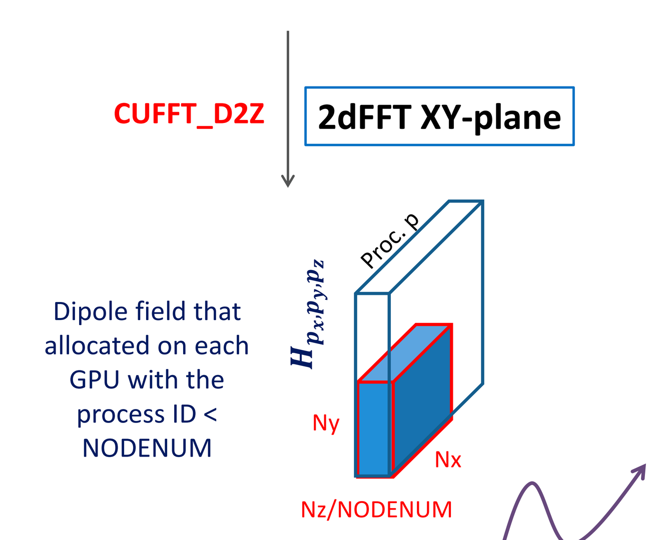
Inverse FFT (x, y, z components):

Fourier transformed demagnetizing tensor

$$\boldsymbol{H}_{p_x,p_y,p_z} = \frac{1}{8N_xN_yN_z}\sum_{j_z=0}^{2N_z-1}\sum_{j_y=0}^{2N_y-1}\sum_{j_x=0}^{2N_x-1} \mathcal{F}K_{j_x,j_y,j_z}\mathcal{F}\boldsymbol{M}_{j_x,j_y,j_z}\, e^{2\pi i(j_x p_x/2N_x + j_y p_y/2N_y + j_z p_z/2N_z)}$$

This dipole field calculation needs the heaviest computational cost in the μMag code because of the all-to-all communications between GPUs.





Transpose kernel

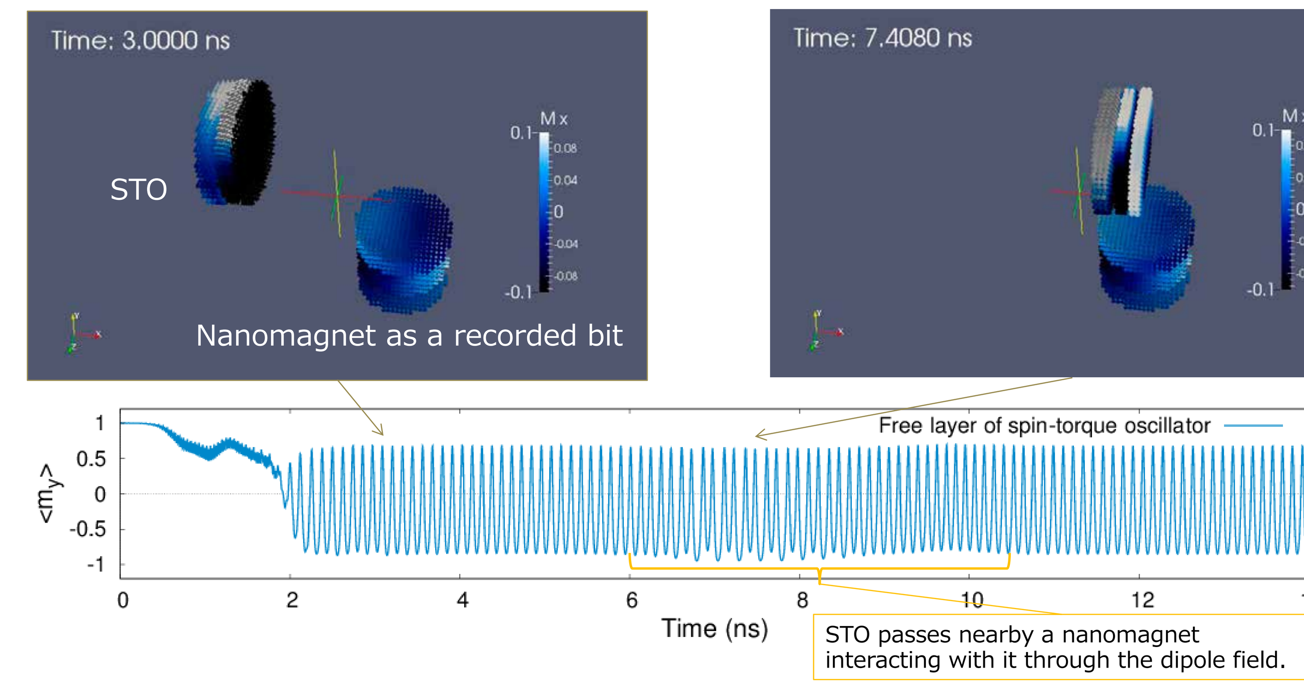
```
__global__ void transposeCoalesced3D_ZXY
(cufftDoubleComplex *odata, cufftDoubleComplex *idata,
int width, int height, int depth){

    __shared__ cufftDoubleComplex tile[TILE_DIM][TILE_DIM+1];

    int xIndex = blockIdx.x * blockDim.x   + threadIdx.x;
    int yIndex = blockIdx.y * blockDim.y   + threadIdx.y;
    int zIndex = blockIdx.z * blockDim.z   + threadIdx.z;

    int xIndexOut = blockIdx.x * blockDim.x   + threadIdx.z;
    int zIndexOut = blockIdx.z * blockDim.z   + threadIdx.x;

    if ( xIndex < width && zIndex < depth ){
        int index_in  = xIndex + yIndex*width + zIndex*width*height;
        tile[threadIdx.x][threadIdx.z] = idata[index_in];
    }
    __syncthreads();

    if ( xIndexOut < width && zIndexOut < depth ){
        int index_out = zIndexOut + xIndexOut*depth + yIndex*depth*width;
        odata[index_out] = tile[threadIdx.z][threadIdx.x];
     }
}
```

This kernel is a 3d extension of a sample code described in CUDA BEST PRACTICE GUIDE v5.0. The Grids & Blocks are: <<<GridDim(Round((Nx+1),TILE_DIM),Ny/NODENUM,Round(2*Nz,TILE_DIM)),BlockDim(TILE_DIM,1,TILE_DIM)>>>.

Functionality Check

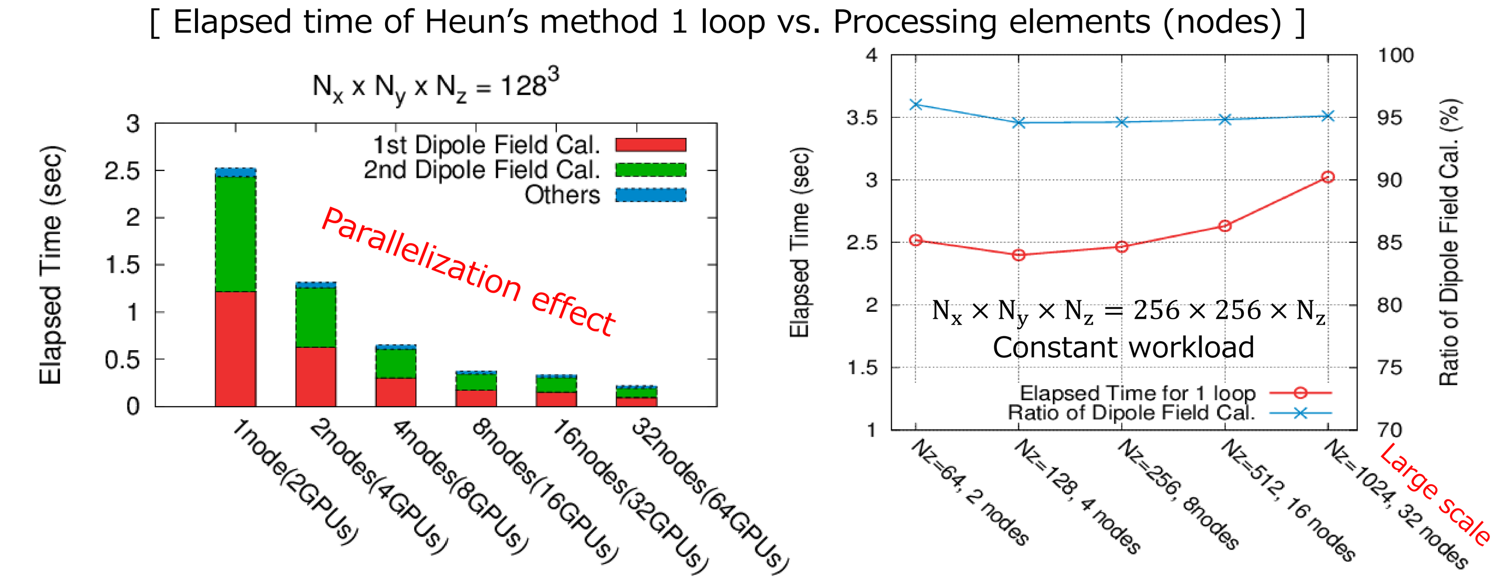
Simulations of magnetization dynamics in several magnetic system verify that μMag models with various couplings are implemented correctly.

Example:
Simulation of a spin-torque oscillator (STO) interacting with a nanomagnet toward the development of next-generation magnetic recording architecture[5,6].



Performance Measurement

[Elapsed time of Heun's method 1 loop vs. Processing elements (nodes)]



Benchmark Environment

IBM System x iDataPlex dx360 M4 computing server
・2 x Intel® Xeon® Processor E5-2690 @ 2.9 GHz / node
・192 GB RAM / node
・2 x NVIDIA® Tesla® K20X GPU / node
・Mellanox InfiniBand SX6536

Software Environment
・RHEL6.3
・NVIDIA CUDA 5.0
・Intel C 13.1
・Intel MPI Library 4.1 for linux

- Significant parallelization effect is validated, but the communication overhead degrades the strong scaling at large processing elements.
- The dipole field calculation occupies 95% of total computing time.
- Large-scale simulations are available.

We have developed a scalable Multi-GPU μMag-simulation code. The implemented code enables us to perform large-scale simulations far beyond single-GPU limitations.

References

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