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A fundumental study on the establishment of calculation machine structure for radiation shielding design of accelerator facilities

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Abstract

The radiation shielding design for the accelerator facilities such as particle medical therapy, academic science, and industrial application is the one of the most important issues for the operation, because they are required to satisfy the limit of radiation exposure dose from these facilities legislated by each regulatory authority. Monte Carlo method is widely used for the shielding design because of ease of constructing three-dimensional geometry and lots of recent technological breakthroughs in computing power. This kind of calculation, however, might require huge parallel machine environment for requirement of evaluation about $1/10^{10}$ to radiation dose at the source term in the facility. The comparison of calculation speed by selected five CPUs on the four assumed facility designs which were a spherical, a cylinder and a rectangular systems, were conducted in order to establish the parallel computing environments. The results of the comparison introduced two CPUs (Intel Core i7-4790K and AMD Ryzen 7 2700x) as good performance for low energy incident radiation. Based on the investigation above, 280 cores, 54 CPUs (216 cores) for Core i7-4790K and 8 CPUs (64 cores) for Ryzen 7 2700x were prepared in parallel computing to establish of calculation machine structure for radiation shielding design for accelerator facilities in order to estimate the doses with reasonable accuracy within a half day for the investigated models.

Keywords : accelerator facility, radiation shield, Monte Carlo calculation, parallel computing, comparison of CPU performance

§1. Introduction

Radiation is a generic name of energetic particles ionizing atoms and molecules. It has been employed for not only basic science but also medical treatment. In particular, X-ray has been used for diagnosis since more than a hundred years ago. Tumor therapy systems using energetic particle as proton, heavy-ion and neutron have been developed and applied in several decades. These particles are generated by accelerators and transported to treatment rooms. The energetic particles interact with accelerator and transport components, a patient body and other items in a treatment room and unwanted secondary radiations like neutron and γ-ray are generated. Shielding these radiations is highly essential for safety to workers and general public. However, optimization of radiation shielding is needed in design of it due to limited space and cost in actual facilities. Huge calculation is required in order to obtain sufficient accuracy in case radiation dose at the boundary of radiation control area is needed less than $1/10^{10}$ that at the radiation source.

A three-dimensional Monte Carlo simulation program PHITS (Particle and Heavy Ion Transport code System) [1] has been used for estimation of radiation dose and optimization of radiation shield in accelerator and medical treatment facilities. This program simulates behavior of each particle in any geometry and give radiation dose and related information. Estimation of radiation dose by PHITS needs just an affordable laptop PC to a simple geometry but much higher computing power than a usual laptop PC for estimation in actual buildings with acceptable accuracy in reasonable calculation time.

As one of techniques to improve computing performance, a parallel computing environment using a PC cluster is employed. It consists of multiple PCs connected with local area network and controlled by MPI (Message Passing Interface) and job schedule software. Rocks [2] is a Linux distribution to organize PC clusters with ease as well as MPICH2 [2] for windows PCs. A PC cluster works as a single high power computer from a user thanks to these kinds of software. One of essential factors of computing performance is CPU model and the number of CPUs.

In this article, we evaluate computing performance of parallel computing environment on estimation of radiation dose according to five CPU models which are generally available and the numbers of CPUs in two simple geometries and two actual radiation shielding design cases.

§2. Conditions for comparisons

For the investigation of the proper calculation conditions, five different CPU models and four typical calculation models were prepared for the comparison of calculation. Consideration of shielding design is usually required a large number of incident particles for accurate estimation of the shielding performance, because leakage of radiation must be enough lower than the prescribed value. So the comparison has been conducted by several types of CPU and calculation models in different numbers of CPU cores in parallel computing.

2.1 Prepared CPUs

Seven kinds of CPU were prepared for the comparison. Table 1 shows the specification of each CPU with abbreviation. The number of cores for each CPU also listed in the table, and that is one of the important for parallel computing as well as the calculation speed, which should have positive correlation to clock frequency of each CPU. There are two manufacturers for CPUs which are AMD and Intel, and the CPU by AMD generally tends to be more affordable than that by Intel. Numbers of cores in our possession are also listed in the table, those of C08 and C47 are more than forty because they were

Table 1 Description of prepared CPU

Name of CPU	Abbreviation	Clock(GHz)	Core	TDP(W)	Manufacturer	Launch date	Possession
Ryzen 7 2700x	R27	3.7	8	105	AMD	Q2 of 2018	8
Ryzen 7 1700x	R17	3.4	8	95	AMD	Q1 of 2017	3
Ryzen Threadripper1950x	THR	3.4	16	180	AMD	Q3 of 2017	1
Core i7-6800K	C68	3.4	6	140	Intel	Q2 of 2016	4
Core i7-4790K	C47	4.4	4	88	Intel	Q2 of 2014	45
Core i7-930	C09	2.8	4	130	Intel	Q1 of 2010	2
Core 2 Duo E6850	CD6	3.0	2	65	Intel	Q2 of 2007	41

used for different calculation of finite elements methods. C09 and CD6 were excluded from the comparison because CD6 was very old CPU with only two cores, and we only owned two CPUs of C09 model which was enough old.

Finally, five CPU, which are Ryzen 7 2700x [4], Ryzen 7 1700x [5], RyzenThreadripper1950x [6], Corei7-6800K [7], and Corei7-4790K [8] (symbols are R27, R17, THR, C68, and C47, respectively), were picked up for the comparison.

2.2 Calculation models for radiation facilities

Table 2 shows calculation models assumed radiation facilities for the comparison. Simple spherical shape geometry was suitable to evaluate each CPU performance for the shielding calculation. Neutron and γ-ray are generally main particles to evaluate for radiation shielding and reaction of neutron with matter generates secondary γ-rays. On the other hand, radiation reaction processes by neutron and charged particle are quite different. Thickness of shielding wall and size for the facility are also important for the calculation. Table 2 shows the typical wall thickness and size of the geometry for the models. Spherical shapes are very simple geometries, a cylindrical shape and a rectangular shape which are examples of actual existing facilities.

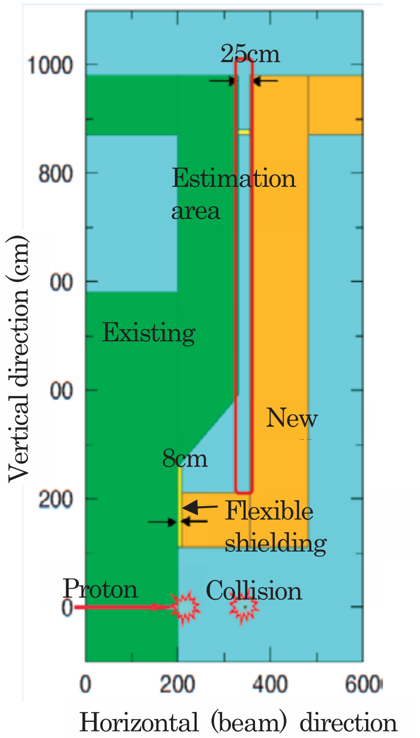

Figure 1 Calculation model for the two buildings.

As an example, Figure 1 shows the geometry of AcH, which is assumed existing accelerator facility to be a cylindrical shape for reducing calculation time.

Finally, five CPUs and four models were selected for the comparison.

Table 2 Calculation models

Abbreviation	Source	Target	Max energy	Wall thickness	Size(footprint)	Geometry
SpL	Proton	Iron	20 MeV	3 m	5 m (radius)	spherical
SpH	Proton	Iron	200 MeV	3 m	5 m (radius)	spherical
AcH	proton	Iron	150 MeV	1.2 m	10 m (radius)	cylindrical
AcL	neutron	-	3 MeV	2 m	20 m × 40m	rectangle

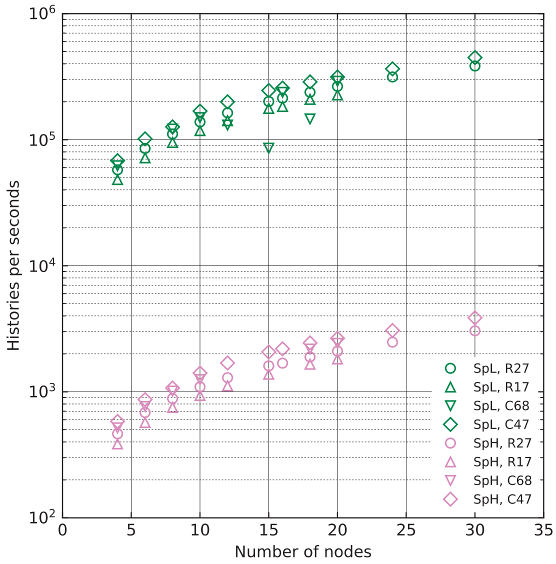

Figure 2 Comparison of calculation speed for various CPUs in simple models (SpL and SpH).

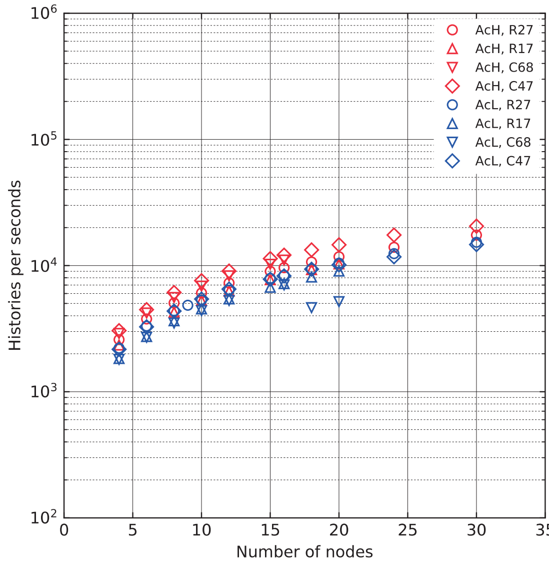

Figure 3 Comparison of calculation speed for various CPUs in models assumed existing facilities (AcH and AcL).

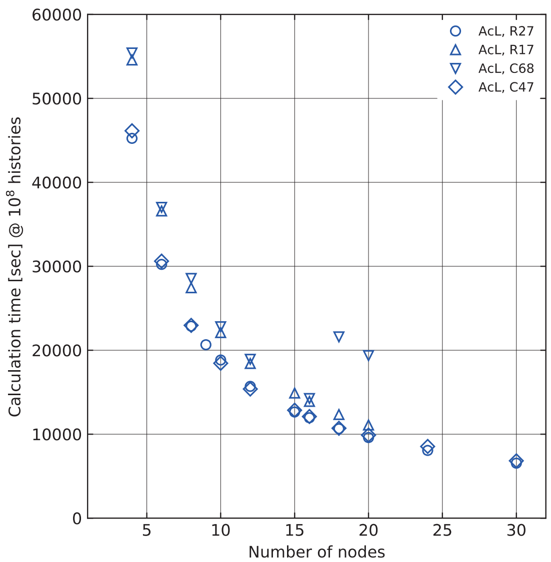

Figure 4 Comparison of calculation time for various CPUs in models assumed the existing facility (AcL).

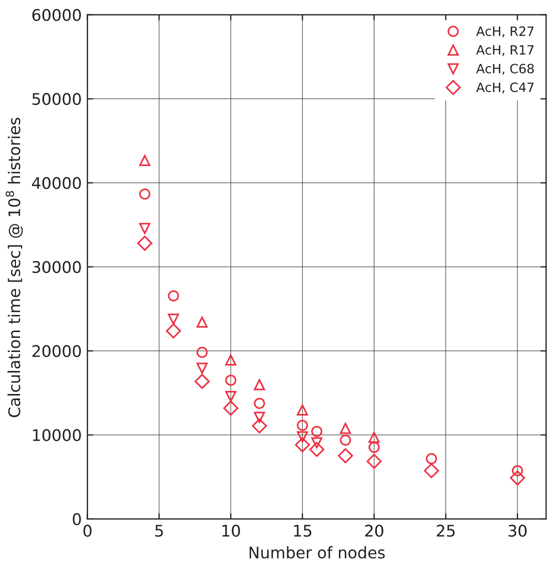

Figure 5 Comparison of calculation time for various CPUs in models assumed the existing facility (AcH).

§3. Comparison of machine performance in several facility models

Calculations for the comparison of CPUs were assumed to be conducted by PHITS program with parallel computing techniques, which were distributed-memory parallel computing using the MPI protocol and shared-memory parallel computing by OpenMP architecture. So, first investigation was focused on the comparison of the parallel computing between distributed-memory parallel method and shared-memory parallel one. Calculations were performed by Ryzen Threadripper 1950x CPU, which had 16 cores in one CPU, with the simple spherical geometry in 3.6×10^8 histories, which were the number of incident particles, without any tallies. In the results, calculation time by distributed-memory parallel computing (calculation time was 5172.88 seconds) was 4.5 times faster than that by shared-memory parallel computing. (the time was 23323.43 seconds)

Secondly, comparisons of calculation speed for four CPUs (R27, R17, C68, and C47) in simple models (SpL and SpH) were conducted in 7.2×10^8 histories without any tallies in 4, 6, 8, 10, 12, 15, 16, 18, 20, 24, and 30 cores for each CPU, respectively. Figure 2 shows histories per second for each core number for the CPU, which was described as "node" with the meaning of calculation core in each CPU for parallel computing. This figure introduced that calculation speed for low energy incident particle (20 MeV proton in SpL mode) was faster than that for high energy particle (200 MeV proton in SpH mode).

Figure 3 shows the comparison of calculation speed for four CPU in models assumed existing facilities. AcH model was cylindrical geometry with 150 MeV proton as incident particles, and AcL model is assumed a BNCT facility in rectangular shape with 20 m × 40 m in footprint size. Incident particle for this model was neutron with certain energy distribution up to several MeV.

Figures 4 and 5 show the comparison of calculation time for four CPUs in models assumed existing facilities (AcL and AcH). Figures 2 to 5 indicate the calculation speed by C47 and R27 CPUs were obviously faster than those by C68 and R17 CPUs. Therefore, the two CPUs, Intel Core - 7 4790K with 4 cores and AMD Ryzen 7 2700x with 8 cores, were selected to establish the machine environment for radiation shield calculation for accelerator facilities.

§4. Discussion and requirement for the calculation

For the selected two CPUs based on fundamental investigation shown in Figures 2-5 in the last chapter, next calculations were conducted in order to establish calculation machine structure for radiation shielding design of accelerator facilities. Because these kinds of calculation might be required huge computing resources, another set of comparisons were investigated with up to 216 cores consisted by 54 CPUs of Core i7-4970K (C47) and 32 cores by 8 CPUs of AMD Ryzen 7 2700x(R27) for assumed calculation models for existing accelerator facilities (AcL and AcH).

Figure 6 shows the calculation time per 10^8 histories for various cores (nodes) for C47 and R27 in AcL model in logarithmic axis. The calculation points by R27 describing as blue circulars were very similar to those by C47 as a diamond shape. These results indicated calculation performance per core (node) of R27 was similar to that of

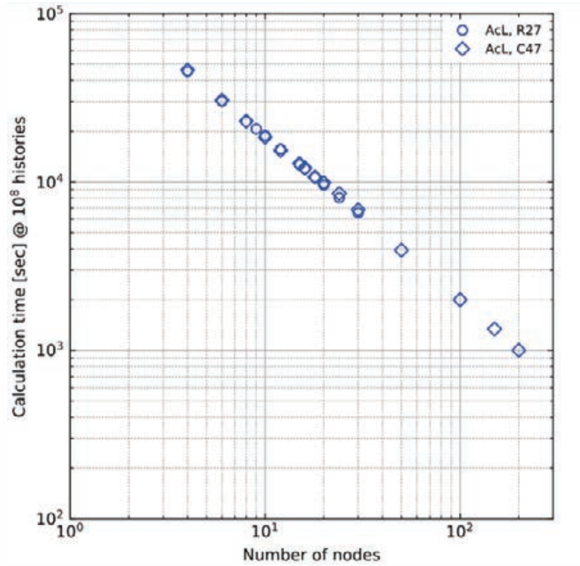

Figure 6 Comparison of calculation time for Ryzen 2700x and Core i7-4790K assumed the existing facility (AcL).

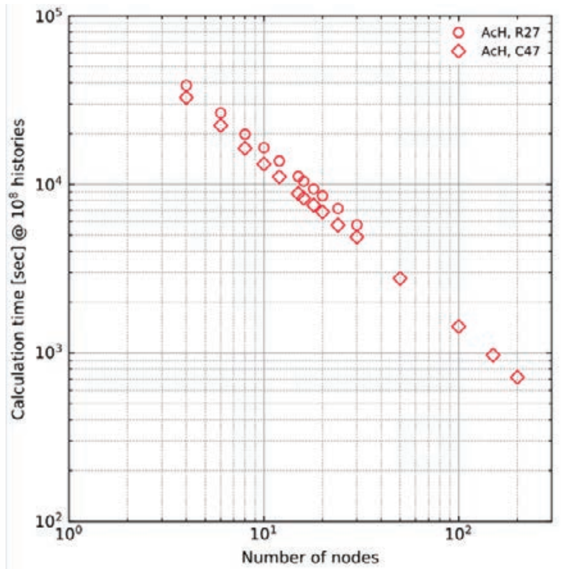

Figure 7 Comparison of calculation time for Ryzen 2700x and Core i7-4790K assumed the existing facility (AcH).

C47, and C47 and R27 might be used as a node in same huge parallel calculation. These results introduced that huge parallel computing machine structure can be consisted C47 with four cores and R27 with 8 cores simultaneously. On the other hands, Figure 7 shows calculation performance for R27 and C47 CPUs in AcH, which were cylindrical geometry with high energy proton as incident sources, while AcL in Figure 6 were large rectangular geometry with low energy neutron as incident sources.

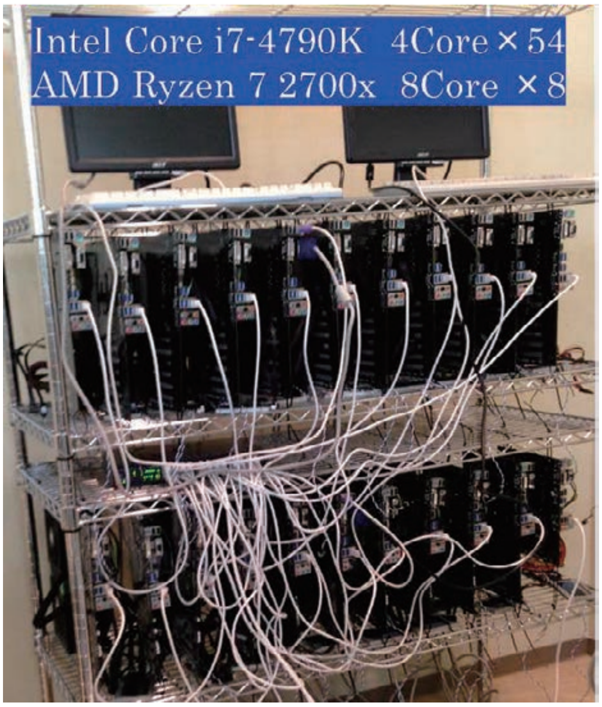

Figure 8 Established calculation machine structure for radiation shielding design of accelerator facilities

Appropriate estimation of numbers of histories for shielding calculation required further investigational calculation with simple tally for AcL and AcH models. Neutron and γ-ray fluence and/or their dose rates at the just outside of the facilities' boundary were calculated by C47 and R27 with 200 cores (nodes) for AcH and with 280 cores for AcH, respectively. Static errors of neutron and γ-ray fluence by the calculation with AcH model were 0.016 and 0.011 in 2.0E9 histories, respectively, which took 16078.92 seconds. This result introduces that the parallel computing machine structure with 200 cores by 50 of C47 CPU can be used for the shieling design of this type of facility within 4.5 hours.

On the other hand, the static error of summation both of neutron and γ-ray dose rate with AcL model was 0.22 in 5.6E9 histories with 42085.71 seconds as calculation time. Even 0.22 as calculation static error is not enough low, it might indicate rough decision of good or need to improve for the object in the design phase. In this meaning, the parallel computing machine structure with 280 cores by 54 of C47 CPU and 8 of R27 CPU might be able to investigate shielding design within 12 hours even for large scale buildings assuming existing facilities.

§5. Conclusion

The comparison of calculation speed by selected five CPUs on the four assumed facility designs which are a spherical, a cylinder and a rectangular systems were conducted in order to establish the parallel computing environments. The results of the comparison introduced two CPUs (Intel Core i7-4790K and AMD Ryzen 2700x) as good performance for low energy incident radiation. Based on the investigation above, 280 cores with 54 CPUs (216 cores) for Core i7-4790K and 8 CPUs (64 cores) for Ryzen 7 2700x were prepared in parallel to establish of calculation machine structure for radiation shielding design for accelerator facilities in order to calculate within a half day for the investigated models.

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Short comment

Radiation shielding calculation is one of the key technologies for the design of radiation facilities as well as low-activation materials. The way of machine setup is described.