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## HIGH ENERGY PHYSICS EXPERIMENTS IN GRID COMPUTING NETWORKS

*The demand for computing resources used for detector simulations and data analysis in High Energy Physics (HEP) experiments is constantly increasing due to the development of studies of rare physics processes in particle interactions. The latest generation of experiments at the newly built LHC accelerator at CERN in Geneva is planning to use computing networks for their data processing needs. A Worldwide LHC Computing Grid (WLCG) organization has been created to develop a Grid with properties matching the needs of these experiments. In this paper we present the use of Grid computing by HEP experiments and describe activities at the participating computing centers with the case of Academic Computing Center, ACK Cyfronet AGH, Kraków, Poland.*

**Keywords:** *High Energy Physics, LHC, WLCG Grid, ACK Cyfronet AGH*

## EKSPERYMENTY FIZYKI WYSOKICH ENERGII W SIECIACH KOMPUTEROWYCH GRID

*Wymagania pod względem dostępu do mocy obliczeniowych używanych podczas wykonywania symulacji i analizy danych w eksperymentach fizyki wysokich energii (FWE) stale rosną wraz z trwającym rozwojem badań rzadkich procesów fizycznych w oddziaływaniach cząstek elementarnych. W najnowszej generacji eksperymentów na budowanym właśnie akceleratorze LHC w ośrodku CERN pod Genewą planuje się wykorzystanie do celów obliczeniowych sieci komputerowe Grid. W celu stworzenia sieci Grid zgodnej z potrzebami tych eksperymentów została powołana do życia nowa organizacja o nazwie Worldwide LHC Computing Grid (WLCG). W niniejszej pracy prezentujemy sposoby i zalety wykorzystania obliczeń w sieciach Grid przez eksperymenty FWE i przedstawiamy działalność WLCG w uczestniczących ośrodkach obliczeniowych, na przykładzie Akademickiego Ośrodka Obliczeniowego, ACK Cyfronet AGH w Krakowie.*

**Słowa kluczowe:** *fizyka wysokich energii, LHC, WLCG Grid, ACK Cyfronet AGH*

### 1. Introduction

The demand for computing resources in High Energy Physics (HEP) experiments is constantly increasing with the development of studies of rare physics processes in interactions of elementary particles. The ever increasing energy of collisions requires

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use of larger and more sophisticated detector systems and new event reconstruction methods, while studies of rare processes increase demand for storage of large amounts of data, since online event selection can not be made precise enough. These high requirements can be currently satisfied only by Grid computing networks managed by international coordinating organizations like EGEE [1] or its brother WLCG [4], created specially for physics experiments planned on the new LHC accelerator. We will discuss here aspects of use of Grid by HEP experiments and will describe current activities at the ACK Cyfronet AGH Computing Center in Kraków, which is a part of Polish Tier2 center in the WLCG organization.

## 2. Problems and experimental methods in High Energy Physics

Physics is trying to provide a description of the world with the help of physics theories and models. They put in order the results of observations and experiments and create physics laws that organize our knowledge in a limited number of compact statements. High Energy Physics is studying the world of basic elements of matter, called elementary particles, and interactions among them. In the current state of theory the world of elementary particles is built from three families of basic objects called quarks and leptons. There are four basic forces governing interactions between elementary particles: electromagnetic, strong, weak and gravitation (Fig. 1).

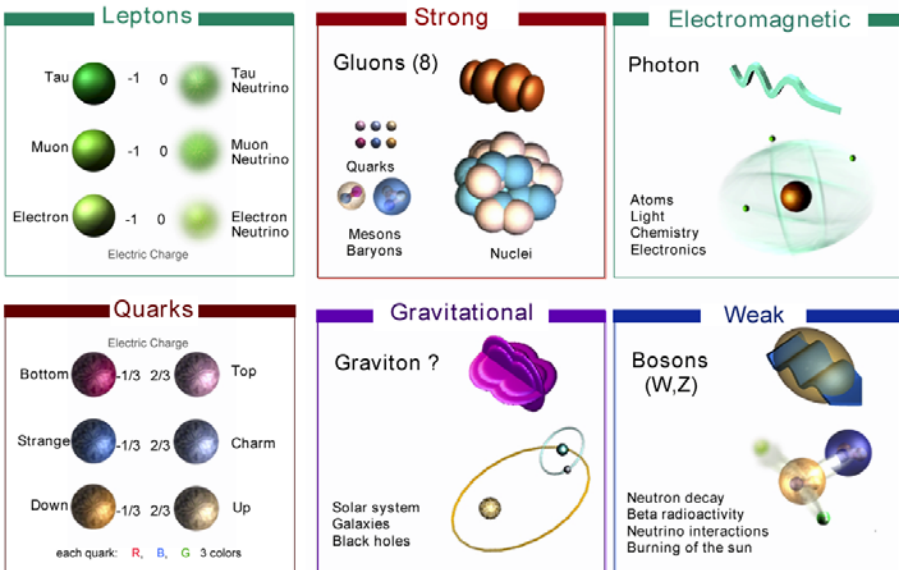


Fig. 1. Particles and forces

One of the fundamental rules used in natural sciences and especially in physics is saying, that if we can explain a phenomenon without introducing a new entity, then this is the preferred way to describe it. This is so called Ockham's rule. In physics we often ask ourselves whether the current description of the world is simple enough, are there ways to explain it with less assumptions? In consequence of this way of thinking in XX-th century we have achieved a series of successful unifications of descriptions of previously seemingly different phenomena: electricity and magnetism, which have been explained in a common Maxwell's theory of electromagnetism. Later, the Weak theory describing force leading to nucleon decay has also been accommodated yielding Electroweak Model. This model, together with the Quantum Chromodynamic (QCD) theory, describing the short range strong nuclear force form the fundamental building blocks of our current understanding of matter – the so called Standard Model. And there are some indications, based on the convergence of the strength of different force couplings at very high energies, that in the future there may be a possibility to unify descriptions of all forces within a single common field theory.

This search for a common theory of elementary particles and forces is the main driving force for studies of particle interactions at ever higher energies. The high energy conditions are achieved by colliding elementary particles pushed to very high energies in devices called accelerators. The properties of particles created in these collisions reveal the structure of matter and reflect the properties of interactions and thus must be carefully measured. These measurements are performed with the use of sophisticated electronic detectors surrounding the point of collision in order to register tracks and properties of particles passing the detector. The type of particles and their properties are reconstructed with the help of complex computer programs; the whole process of registering collisions, storing data from detectors and reconstruction of particle properties demands use of huge amounts of computing resources.

### **3. Computing resources in HEP experiments**

High Energy Physics experiments use computers for the preselection and recording of detector data online, for storage of both the raw detector data and the data coming from all processing steps of reconstruction and for the reconstruction process itself. In addition to processing real detector data, huge amounts of simulated events are generated even before the real data become available. The simulations are done in two steps, the first one simulating the process of particle generation according to a model of the studied processes. This phase allows also studies of different models and theories by comparing results of real physics processes reconstructed from real data with those generated according to physics models. In the second step a response of the detector to the passage of generated particles is simulated. This type of simulations is used to understand the response of the detector to the passage of outgoing particles, to calculate the acceptance of the detector and efficiency factors of the reconstruction process. These parameters are later used to correct the raw reconstruction results for the inefficiencies of the reconstruction process. Calculations of this kind are also

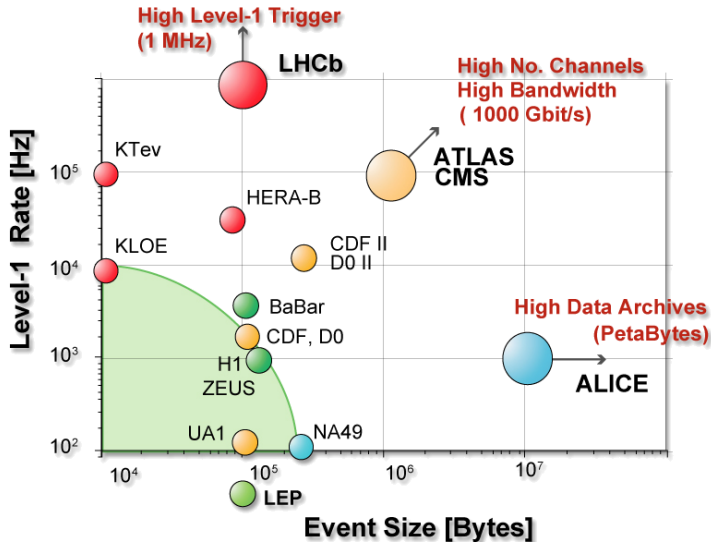
used many times at the early stage of the experiment design in order to optimize performance of the detector in areas most important for the planned experiment.

The total amount of data used for experimental analysis is huge and is increasing all the time with the increasing energy of processes studied. This is due to the increasing complexity of newly constructed detectors and the general tendency to study rare processes in order to learn about the physics in new energy domains, not accessible with the present accelerators. In this situation experiments need to sift through millions of events, that have already been studied at lower energies, before they can register a rare event of particular interest. The frequency of rare processes may be lower than that of common events even by 11 orders of magnitude. The selection is performed mostly online, in order to avoid storing too much of the uninteresting data, but even then the storage requirements of HEP experiments are exceeding the capacity of any single computer cluster in the world.

## 4. New breed of experiments on Large Hadron Collider

The new breed of HEP experiments at the Large Hadron Collider (LHC) creates a new challenge in providing computing resources for data storage and analysis. LHC is a new collider accelerator under construction at CERN – the European Organization for Nuclear Research center near Geneva on the border between France and Switzerland. In the primary mode of operations this accelerator will collide protons at the total energy of 14 TeV – 7 times higher energy than it was available until now. There will be 4 big experiments located on this accelerator: ATLAS [5], CMS [6], ALICE [7] and LHCb [8]. ATLAS detector is the largest among them – its size is 46 m length, 25 m width and 25 m height. The total mass of the detector is 7000 tons. It is composed of several main elements each designed for specific purposes: multicomponent Inner Detector inside the magnetic field of the Solenoid magnet for charged particle tracking and momentum measurements, Electromagnetic and Hadronic Calorimeters for energy measurements of neutral and charged particles and the Muon chambers with Toroid magnetic field for measurements of muon particles. Specialized hardware and computers are used to read out information from this huge detector. After compression the raw data of an average event, written to disk, will occupy 1.6 MB of storage space. LHC accelerator operates at a very high frequency of  $10^9$  particle collisions per second making it impossible to register all of them. However since physics experiments are interested only in special events of rare processes that happen not so often it is possible to apply a system of filters leading to an efficient selection of interesting events and reduction of the amount of raw data stored on disk. These filters are called trigger systems and they are one of the crucial elements of the online data acquisition. The ATLAS experiment has implemented three step trigger with the capacity to reduce the rate of event acquisition by 5 orders of magnitude, down to the level of 100 Hz [9]. The other LHC experiments have similar data acquisition systems. A comparison of their operating parameters at the Level-1 trigger is shown in Figure 2.

The trigger systems of the LHC experiments break records in all aspects: the frequency of event acceptance, 1 MHz (LHCb), the size of the raw event, 10 MB (ALICE) and the total rate of data transfer, 1000 Gbps (ATLAS, CMS) [10].



**Fig. 2.** Properties of raw data transfers from Level-1 trigger in LHC experiments and a comparison with earlier HEP experiments

It is estimated that all 4 experiments will require storing of  $15\text{--}20 \times 10^{15}$  (PetaBytes) of data per year during their operations and data analysis, at the same time using computing power equivalent to some 100,000 PC computers. This level of computing power cannot be easily provided and managed by a single computing center. An additional argument for using distributed computing resources was also to make them more easily available for international collaborations of physicists, members of LHC experiments, coming from physics institutes located all over the world. The answer to this challenge was to use a newly developed information technology – the so called Grid.

## 5. WLCG Grid for LHC experiments

The idea of Grid computing emerged at the end of the 90's of the XX-th century. The scale of computing projects started to exceed the capacity of a single computing center while at the same time there was an increasing need in easier access to the data and for sharing data processing tasks among members of large international collaborations of physicists working together. Since computing resources at different locations are usually not used full time by local communities, sharing them with other computing projects increases efficiency of use of the hardware. This process of sharing resources

would not be possible without rapid developments of computer networks that provided fast 1–10 Gbps connections at a moderate cost.

Grid is a way to organize resources to enable sharing them among different projects and organizations. The key components of Grids are computer networks that provide connectivity, Grid software, the so called middleware, the standards and infrastructure services that provide a common base for Grid wide operations. The project for building Grid for LHC experiments (LCG) [11] was approved by CERN Council in September 2001. The project's goal was to develop a distributed production prototype service that would be later extended to a full world-wide production Grid system. During the last years the LCG project has developed a large hardware infrastructure base which is currently coming from three project groups: the Enabling Grids for E-science (EGEE) European project [1], the Open Science Grid (OSG) project [2] developed in US, and Nordic Data Grid Facility (NDGF) [3] from North European countries. These different at one point projects are now developing inter Grid gateways and common middleware to form Worldwide LHC Computing Grid (WLCG) [4].

Computing centers participating in the WLCG Grid are classified according to their size and functionality they declare to provide. The central Tier0 site is located at CERN since its main function is to register raw detector data coming from LHC experiments. In addition, Tier0 performs also the first step of data calibration and reconstruction and then distributes both the raw and reconstructed data to Tier1 sites. There are currently 10 Tier1 sites located all over the world. Their main function is to provide storage capacity for data coming from all processing steps both on real and simulated data. The Tier1 sites cooperate with and coordinate groups of associated Tier2 sites, that are smaller but more numerous and thus provide almost the same computing and storage capacity as sites of a higher rank. Polish sites of the ACK Cyfronet AGH in Kraków, ICM in Warsaw and PCSS in Poznań form a single distributed Tier2 that supports all LHC experiments and is associated with the German Tier1 site at FZK Karlsruhe. The FZK "cloud" is one of the larger groups in WLCG. In the same group there are also computing clusters from Czech Republic, Austria, Switzerland, and Germany.

The process of acquiring computing resources for use by LHC experiments within WLCG Grid is coordinated by several management bodies such as Computing Resource Review Board, Grid Deployment Board and Management Board. In this process WLCG Management signed Memorandum of Understanding with National Funding Institutions, that finance computing centers [12]. Based on their financial plans, the Computing Centers declare computing and storage resources they expect to provide in the next several years and the Management Board of WLCG compares the capacity declared with that required by LHC experiments and eventually takes some corrective actions. Currently, a plan for years 2007–2012 is available (Fig. 3), which predicts a ten-fold increase in computing and storage resources over these years, reaching eventually in 2012 the total of 300,000 kSi2K CPU and 150 PBytes of disk

storage [13]. Polish sites will provide about 2% of the total computing power in proportion to the engagement of Polish scientists in the LHC experiments.

Summary with Requ. Balance	2007	2008	2009	2010	2011	2012		SUM 2008	SUM 2009	SUM 2010	SUM 2011	SUM 2012
CPU (kSI2K)	14894	37563	61692	101737	126523	146130	Offered	37563	61692	101737	126523	146130
							Required	39590	69600	114720	152230	191810
							Balance	-5%	-11%	-11%	-17%	-24%
Disk (Tbytes)	7221	20221	35222	60008	79675	93821	Offered	20221	35222	60008	79675	93821
							Required	22965	40179	71000	96791	123952
							Balance	-12%	-12%	-15%	-17%	-24%
Tape (Tbytes)	6503	21298	40329	65438	88837	106775	Offered	21298	40329	65438	88837	106775
							Required	24530	46260	78864	114610	152396
							Balance	-13%	-13%	-17%	-22%	-29%

Summary Tier2s with Requ. Balance	2007	2008	2009	2010	2011	2012		SUM 2008	SUM 2009	SUM 2010	SUM 2011	SUM 2012
CPU (kSI2K)	21986	45486	68432	106753	135970	153850	Offered	45486	68432	106753	135970	153850
							Required	47960	80750	164540	218720	278010
							Balance	-5%	-15%	-35%	-38%	-44%
Disk (Tbytes)	4641	12125	21728	33187	42085	47703	Offered	12125	21728	33187	42085	47703
							Required	14579	23023	34243	47903	61963
							Balance	-17%	-6%	-3%	-12%	-23%
Tape (Tbytes)	0	0	0	1500	2000	3000						

Poland, Polish Tier-2 Federation	2007	2008	2009	2010	2011	2012	Split 2008	ALICE	ATLAS	CMS	LHCb	SUM 2008
CPU (kSI2K)	650	1250	1780	2635	3265	3940	Offered	265	407	241	237	1250
							% of Total	2%	2%	3%	5%	3%
							Offered	15	113	74	0	202
Disk (Tbytes)	60	202	340	599	808	1019	Offered	15	113	74	0	202
							% of Total	1%	1%	1%	0%	1%
							Offered	15	113	74	0	202
Nominal WAN (Mbits/sec)	1000	1000	2000	2000	2000	2000						

Fig. 3. WLCG Resources, plans for 2007–2012 (summary of all resources, Tier2 sites and the Polish computing centers)

One of the basic elements of computing Grid is connectivity between individual computer clusters. This connectivity allows exchange of data and information and is provided by computer networks. In the WLCG Grid the requirements with respect to the quality of network connections are especially important, since one of the basic functions of this Grid service for LHC experiments is a distribution of data and providing access to this data for physicists doing analyses. Fortunately the quality and bandwidth of general purpose and scientific networks in Europe has been constantly improving since many years thanks to the infrastructure projects like GEANT and its continuation GEANT2. Polish Tier2 sites are in good position since in Poland the national project Pionier provides 10 Gbps connectivity between major Polish cities. In addition, a dedicated 1 Gbps link (VLAN) has been created that connects Polish Tier2 sites with our Tier1 partner FZK Karlsruhe for use by HEP experiments.

It is not possible to design and construct such a big enterprise like WLCG Grid in a single step. The services have to be constructed, tested and improved step by step. Right from the beginning series of tests were run on WLCG structures [14]. The most intensively tested were network connections and file distribution and storage services at Tier0 and Tier1 sites. The goal was to achieve export rates of 1.6 GBps out of CERN, which was not easy. Only in the recent (February 2008) common test of all LHC experiments, called Combined Computing Readiness Challenge (CCRC'08), the export to Tier1 sites reached 2 GBps in a peak and was kept at the level of 1.5 GBps for several days. Another important element that needs to be cared for is the quality and continuity of Grid services. This element of functioning of services is so important that a special monitoring tool called SAM have been developed for the purpose of testing and getting quality measures of different computing and storage services running on the Grid at different centers.

Poland, Polish Tier-2 Federation	AMD64.PSNC.PL	95%	93%	85%	93%	91%
	CYFRONET-IA64	97%	97%	95%	97%	87%
	CYFRONET-LCG2	94%	94%	71%	84%	87%
	egee.man.poznan.pl	88%	88%	66%	78%	91%
	WARSAW-EGEE	97%	97%	93%	99%	99%
<b>PL-TIER2-WLCG</b>		94%	94%	82%	90%	91%
Portugal, LIP Tier-2 Federation	LIP-Coimbra	4%	44%	94%	98%	82%
	LIP-Lisbon	11%	35%	88%	98%	37%
<b>PT-LIP-LCG-Tier2</b>		7%	39%	91%	98%	60%

**Fig. 4.** Availability and reliability measures for Polish Tier2 sites in January 2008 (left column numbers) and availability for the last 3 months of year 2007 (right column numbers)

The Memorandum of Understanding for the centers of Tier1 and Tier2 rank specifies not only the types of services that they will need to provide but also the quality measures, the availability and reliability, that these services should achieve. The availability is the percentage of total time when the service is available, and the reliability is the percentage of time when service is available and site is not in the officially announced downtime. These factors are now continuously monitored, published and discussed at WLCG Grid Deployment Board meetings [15]. Polish Tier2 sites are improving their quality of service staying recently at a good level of 90–95% uptime (see Fig. 4), which is what is required for Tier2 sites.

## 6. WLCG activities at ACK Cyfronet AGH Computing Center

The ACK Cyfronet AGH Computing Center in Kraków together with ICM in Warsaw and PCSS in Poznań form the Federated Polish Tier2. Since 2003 the LHC experiments ATLAS and LHCb and later on the ALICE experiment have been running simulation production at Cyfronet and preparing Grid infrastructure for the start of LHC operations. The accounting of the amount of CPU time used on Polish Tier2 sites is presented in Figure 5.

The plot shows that currently Cyfronet delivers the largest share of resources amongst the Polish Tier2 sites. Most of them are used by the ATLAS experiment. Cyfronet cluster is seen also as a significant contributor of computing resources in the world-wide WLCG classification (see Fig. 6) delivering 2% of the CPU time used by WLCG in 2006–2007 [16], in proportion to the engagement of Polish scientists in LHC experiments.

The production of simulations is a test of the Grid system on its own. In addition, the WLCG Grid is constantly developing and testing new features and services according to requests coming from the experiments. Also the experiments themselves continue to improve their own software and computing services. These also need to be tested. ACK Cyfronet AGH participates in production of simulated data and all the tests that the WLCG and experiments are undertaking. The recent ATLAS tests of data transfer between Tier0, Tier1 and Tier2 sites proved that the whole Tier1



FZK group, and – in particular – ACK Cyfronet AGH site, are up to date with the configuration of Grid services by running data transfers with full speed and high efficiency. Figure 7 illustrates results of the recent tests, where Tier2 sites in FZK group received green acceptance rates [17].

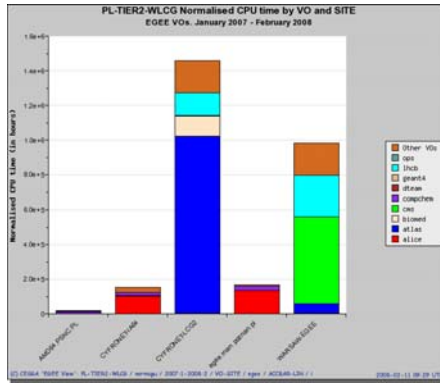


Fig. 5. The distribution of CPU time used on Polish Tier2 sites by different experiments

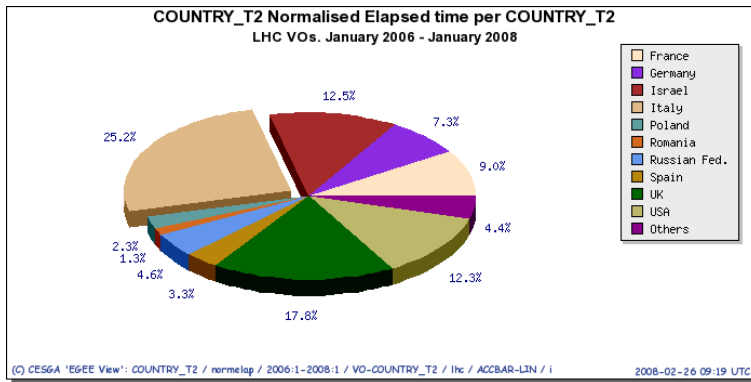


Fig. 6. Top 10 CPU time providers among WLCG Tier2 sites in 2006–2007

## 7. Start up plan and perspectives of LHC in 2008 and later

In the next several months, before the start of real data taking, the experiments will do final tests. These tests will continue until the LHC starts delivering physics quality particle beams. This is expected to happen some time in the Fall 2008, after a 1–2 months period of LHC commissioning.

The future of LHC computing is determined by a constant increase in the amount of data received from the detectors [18]. With time the LHC accelerator will improve

its performance in delivering larger and larger numbers of collisions, allowing the studies of rare processes, whereas requiring larger and larger amounts of processing and storage resources. In 2012 it is expected that we will need to handle 300 times more data than we will have received in 2008.

ASGC	AE-ATLAS	TW-FTT										
BNL	AGLT2	BU	IU	OU	SMU	SWT2	SLAC	UMICH	WBC			UC
CNAF	LNF	MILANO	NAPOLI	ROMA1								
FZK	CSCS	CYF	DESY-HH	DESY-ZN	FREIBURG	FZU	HEPHY-UIBK	LEZ	WUP			
LYON	HEBING	CPPM	LAL	LAPP	LPC	LPNE	NIPNE_02	NIPNE_07	SACLAY	TOKYO		
NDGF	IST2											
PIC	IFAE	IFIC	LIP-COIMBRA	LIP-LISBON	UAM							
RAL	BHAM	BRUN	CAM	DUR	EDINBURGH	ECDF	GLASGOW	LANCS	LIV	MANC		
SARA	IHEP	IIEP	JINR	NIKHEF	FNPI	SINP						
TRIUMF	ALBERTA	MCGILL	SPU	TORONTO	UVIC							

**Fig. 7.** Results of the recent ATLAS Data Transfer tests on the WLCG Grid. All sites in FZK cloud are green (sites passed tests) except for a new site from Austria.

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