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CPU Performance Optimizations of Virtualized Compute Resources in the CERN Cloud Service

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The “20% overhead” problem

- On our batch full node VMs we noticed that the HS06 rating was ~20% lower than on the underlying host
  - Full node VMs are needed to the limit of the total number of hosts in LSF
- Smaller VMs behaved much better: ~8%
  - The sum of simultaneous HS06 runs on 4x 8-core VMs on a 32-core host
  - Better, but still pretty high
- IN2P3 reported significant performance penalties for ATLAS MC jobs when EPT* was switched on
  - 26% vs. 6% in wall clock time for EPT on vs. EPT off compared to bare metal
  - Surprising as EPT is supposed to make things faster

***EPT:** Extended Page Tables is Intel’s implementation of a hardware-assisted virtualization technology for page table management (secondary address translation or nested pages). AMD’s implementation is called RVI (Rapid Virtualization Indexing).

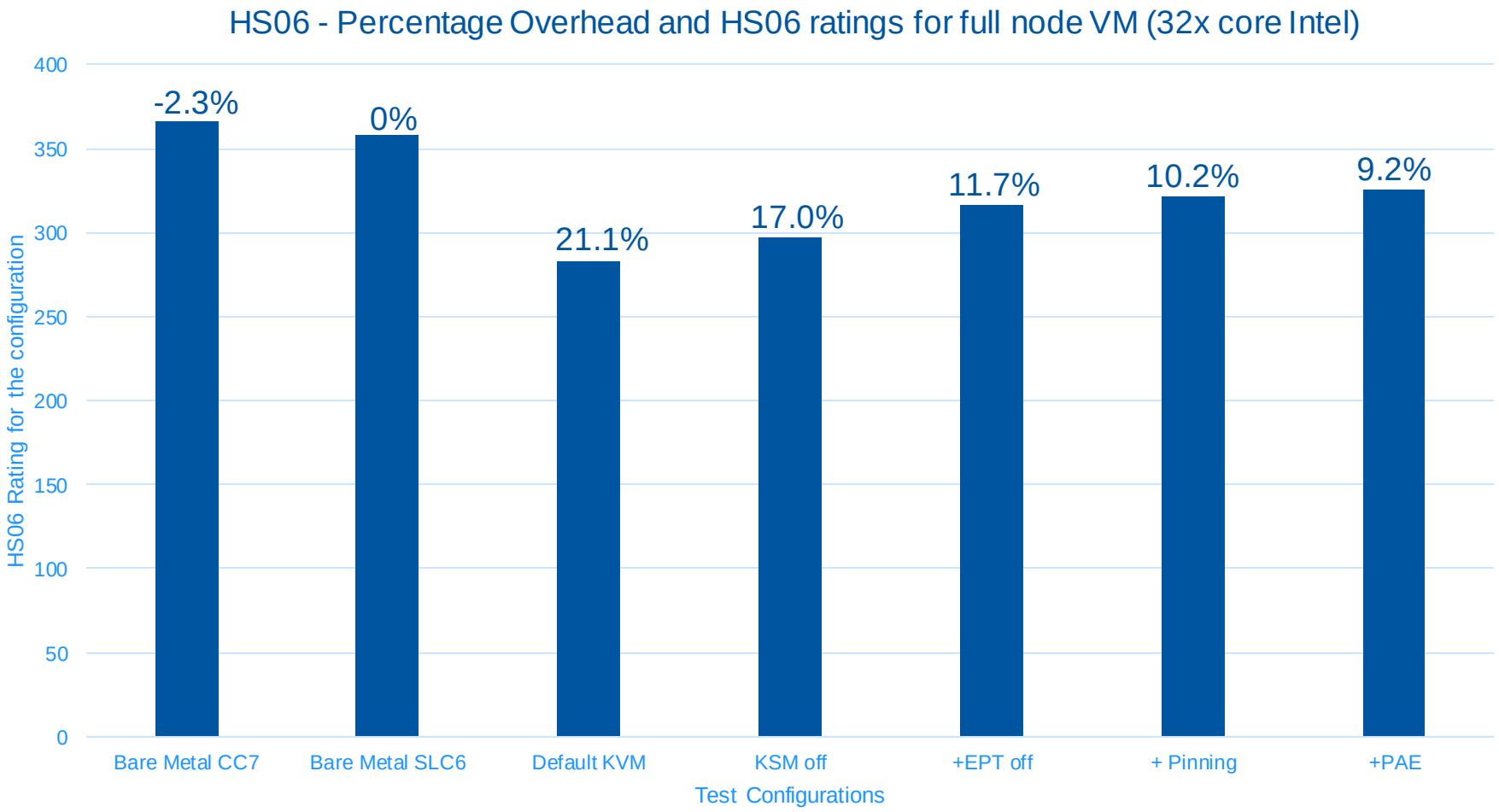
HS06 on virtual batch workers

Type 1: Intel(R) Xeon(R) CPU E5-2650 v2 @ 2.60GHz

HWDB HS06	VM Size (cores)	Per VM HS06	Total HS06	Overhead
357±16	4x 8	82.3±11	329	7.8%
	2x 16	150±5	300	16%
	1x 32	284±11	284	**20.4%**

- One hardware type
  - 30x 32-core Intel boxes
- Default settings, no tuning
  - Except for host pass-through

VM Tuning Potential



First Optimisations

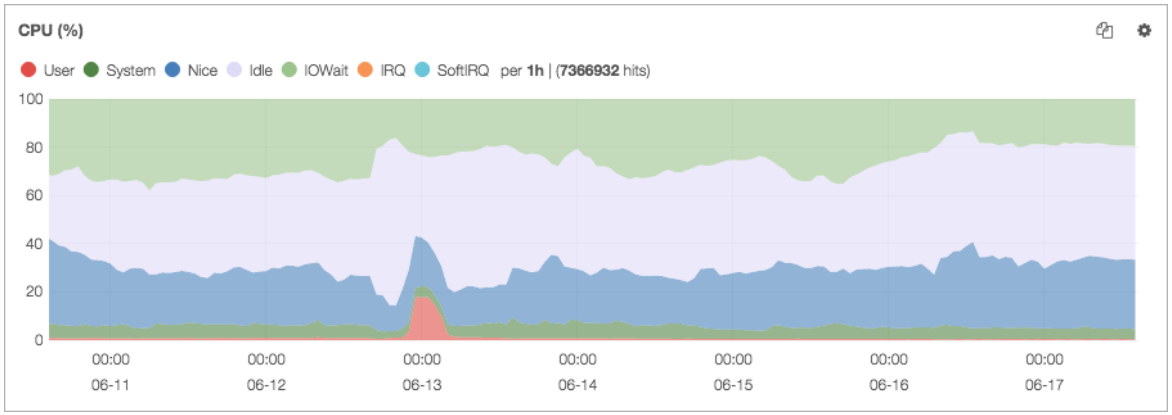
Type 1, before:

HWDB HS06	VM Size (cores)	Per VM HS06	Total HS06	Overhead
357±16	4x 8	82.3±11	329	7.8%
	2x 16	150±5	300	16%
	1x 32	284±11	284	20.4%

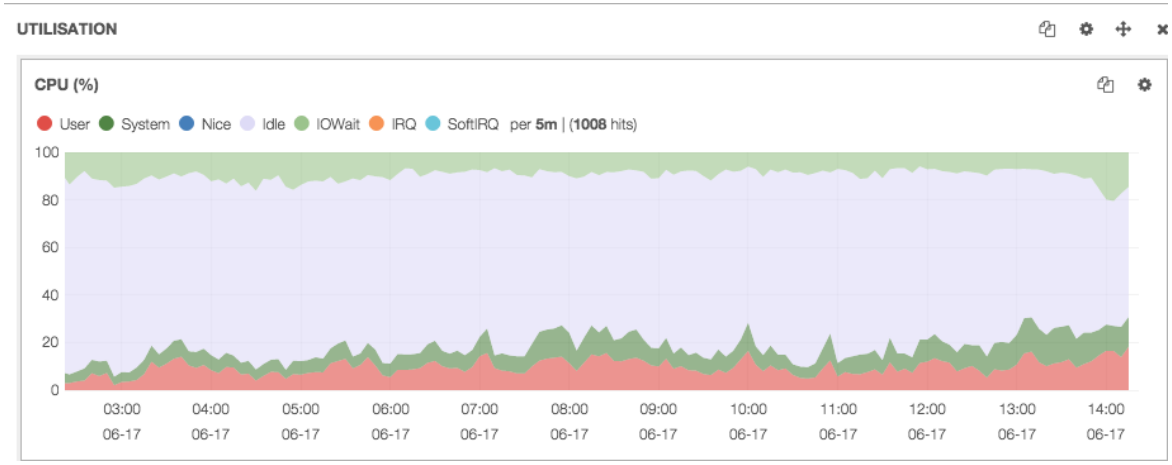
Type 1, after:

HWDB HS06	VM Size (cores)	Per VM HS06	Total HS06	Overhead	Overhead Reduction
357±16	4x 8	87±11	348	2.5%	68%
	2x 16	163.5±1	327	8.4%	52%
	1x 32	311±1	311	12.9%	37%

Swapping Hosts Detour (1/4)



ATLAS T0 batch VMs show IOwait 20-30%



Hypervisor in IOwait as well … swapping!

Swapping Hosts Detour (2/4)

- Why do the servers swap?
  - 2x 31GB should leave 2GB for the hypervisor
  - 1.5GB used by “something”, even on empty hypervisor

```
[root@p05792986e53504 ~]# echo 3 > /proc/sys/vm/drop_caches && sync && free -wm
              total        used        free      shared     buffers       cache   available
Mem:          64160        1315       61272         216           0        1571       61217
Swap:             0           0           0
```

```
[root@p05792986e53504 ~]# grep SUnreclaim /proc/meminfo
SUnreclaim:      1292408 kB
```

Swapping Hosts Detour (3/4)

- Where's my memory?

root@p05792986e53504:/proc

```
Active / Total Objects (% used)    : 18586976 / 20117301 (92.4%)
Active / Total Slabs (% used)      : 304473 / 304473 (100.0%)
Active / Total Caches (% used)     : 78 / 105 (74.3%)
Active / Total Size (% used)       : 1253908.57K / 1365327.83K (91.8%)
Minimum / Average / Maximum Object : 0.01K / 0.07K / 8.00K

  OBJS ACTIVE  USE OBJ SIZE  SLABS OBJ/SLAB CACHE SIZE NAME
16575360 15277296  92%    0.06K 258990       64   1035960K kmalloc-64
2287265 2111233  92%    0.05K  26909       85    107636K shared_policy_node
177152 176804  99%    0.03K   1384      128      5536K kmalloc-32
135184 135016  99%    0.07K   2414       56      9656K Acpi-ParseExt
131580 130730  99%    0.02K    774      170      3096K fsnotify_event_holder
115712 113197  97%    0.01K    226      512       904K kmalloc-8
108800 105124  96%    0.02K    425      256      1700K kmalloc-16
 65646  65399  99%    0.19K   1563       42     12504K dentry
 59058  58939  99%    0.08K   1158       51      4632K selinux_inode_security
 58644  58133  99%    0.11K   1629       36      6516K sysfs_dir_cache
 41734  13153  31%    0.57K    768       56     24576K radix_tree_node
 28672  28537  99%    1.00K    896       32     28672K xfs_inode
 26368  22520  85%    0.12K    422       64      3376K kmalloc-128
 24990  23701  94%    0.19K    595       42      4760K kmalloc-192
```

Swapping Hosts Detour (4/4)

Using systemtap to find slab cache user

```
#! /usr/bin/env stap

global slabs

probe vm.kmem_cache_alloc {
  slabs [execname(), bytes_req, call_site, caller_function]<<<1
}

probe timer.ms(1000)
{
  dummy = "";
  foreach ([name, bytes, site, call_function] in slabs) {
    if (dummy != name)
    printf("\nProcess:%s\n", name);
    printf("\nCall Site:%x - Call  Function:%s\n", site, call_function);
    printf("Slab_size:%d\tCount:%d\n", bytes,
                        @count(slabs[name, bytes, site, call_function]));
    dummy = name;
  }
  delete slabs
  printf("\n----------------------------\n\n")
}
```

```
…
Slab_size:64        Count:6
Slab_size:64        Count:8
Slab_size:64        Count:1
Slab_size:64        Count:1
Process: ksmd
Call Site: …
Slab_size:64        Count:518400
Slab_size:64        Count:550
Slab_size:64        Count:3
Slab_size:64        Count:1
Slab_size:64        Count:3
Slab_size:64        Count:5
Slab_size:64        Count:10
Slab_size:64        Count:9
Slab_size:64        Count:17
Slab_size:64        Count:13
Process: ksmd
Call Site: …
Slab_size:64        Count:697500
Slab_size:64        Count:16
Slab_size:64        Count:3
Slab_size:64        Count:24
Slab_size:64        Count:280
Process: ksmd
Call Site: …
Slab_size:64        Count:696386
Slab_size:64        Count:1
Slab_size:648       Count:2
Slab_size:648       Count:2
Slab_size:64        Count:1
…
```

This memory is not freed when KSM is disabled!

Hardware Type Differences

Type 1 optimised:

Intel(R) Xeon(R) CPU E5-2650 v2 @ 2.60GHz

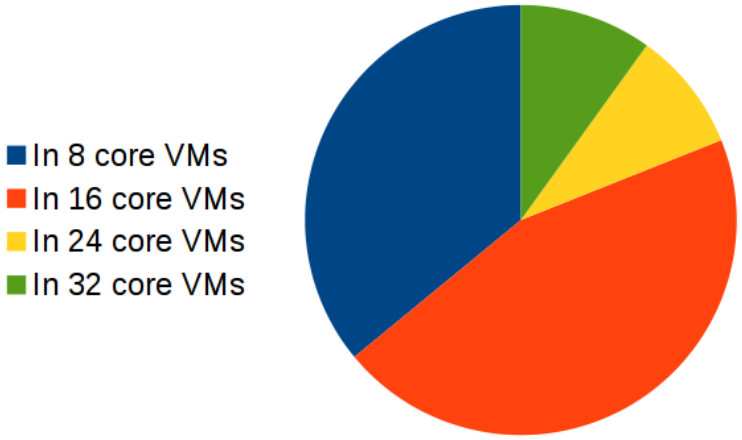
HWDB HS06	VM Size (cores)	Per VM HS06	Total HS06	Overhead	Overhead Reduction
357±16	4x 8	87±11	348	2.5%	68%
	2x 16	163.5±1	327	8.4%	52%
	1x 32	311±1	311	12.9%	37%

Type 2 optimised:

Intel(R) Xeon(R) CPU E5-2630 v3 @ 2.40GHz

HWDB HS06	VM Size (cores)	Per VM HS06	Total HS06	Overhead	Overhead Reduction
344±1	4x 8	84±7	336	2.3%	65.7%
	2x 16	161±2	322	6.4%	22%
	1x 32	279±4	279	19%	13.6%

Core Distribution & Effective Impact



Take into account the core distribution over VM flavors to determine real loss (7-8%)

Small VMs (8 or 16 cores)	Large VMs (24 or 32 cores)
Closer to bare metal performance	Better memory flexibility
Closer to LSF limitations (less of a problem after instance split)	Higher performance penalty

General virtualization issue?

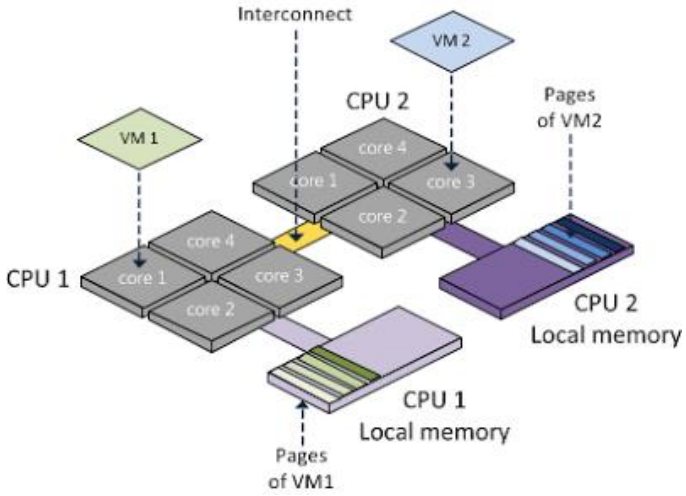
- Crosscheck w/ SLC6 VMs on Hyper-V
  - 0.8% HS06 loss on 4x 8-core
  - 3.3% HS06 loss on 1x 32-core SLC6 VM

- No general virtualization overhead issue!
  - Rather a feature or configuration issue

- What's the difference between the VMs on Hyper-V and the ones on KVM?

NUMA

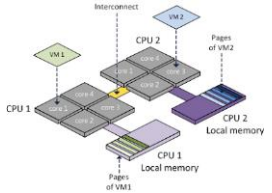
- Hyper-V VMs “see” underlying NUMA architecture



- Hyper-V VMs have vCPUs pinned to physical NUMA nodes
  - Pinned to sets that correspond to physical NUMA nodes

- In OpenStack, wider support for this comes with the release we currently prepare to deploy (Kilo)
  - Juno has some NUMA support as well
  - Consciously not configured, then disabled after ATLAS T0 incident (aka the “50% overhead” problem …)

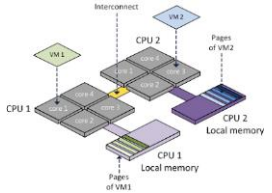
NUMA in the lab



- Standard SLC6 VMs on CC7 hypervisors …
  - "Production" tuning plus extras (e.g. KSM off, numad off)
  - Manual VM configuration: 4 NUMA nodes, 1-on-1 pinning

- … reduce the loss to ~3% of the bare metal performance as listed in the hardware DB
  - 16-core and 8-core VMs even better (within error bar)

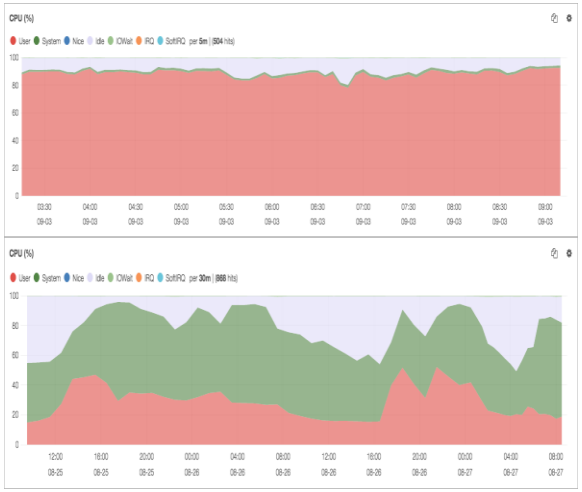
NUMA: from lab to prod



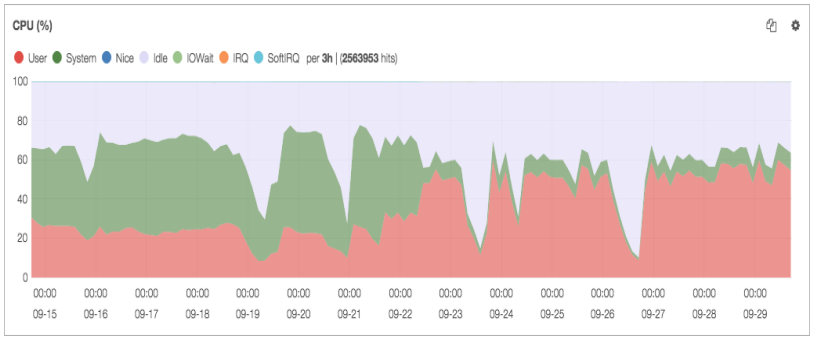
- Reproducible on NUMA-aware batch VMs!
  - ~3% with KSM off, system services off
  - ~4.5% with KSM off, system services on
  - ~5% with KSM on, system services on
- Need to assess impact of KSM in more detail
  - Needed in production for now
  - Tuning possible (NUMA-aware KSM, scanning frequencies)
- System services overhead around 1-2%
  - Hardware DB value measured without services
  - We need more statistics
  - Investigations on virtual and physical hardware ongoing

Issue w/ extremely slow nodes

- Small fraction of jobs 10x slower
  - Painful for the experiment workflows
  - VMs look OK, actually pretty good
  - Hosts: 30-50% system load, >100k IRQ/s (mostly TLB shoot-downs)



- Load attributed to qemu-kvm
  - ‘perf top’: 90% in _raw_spin_lock
  - ‘systemtap’: paging64_page_fault and kvm_mmu_pte* …



→ “EPT off” side-effect!

(not seen by HS06 nor in our pre-deployment tests)

EPT revisited

- Hardware support for management of guest page tables
  - Available in all modern processors (SLAT, NPT, RVI)
  - Avoid shadow page tables, i.e. double maintenance in software ("slow job" effect: s/w needed to do things that could be done in h/w)
- HS06: TLB misses can be more expensive with EPT on than with shadow page tables
  - Each page request in the guest translates into multiple page table walks in the host
  - NPT on/off on AMD made no difference! page table walk cache?

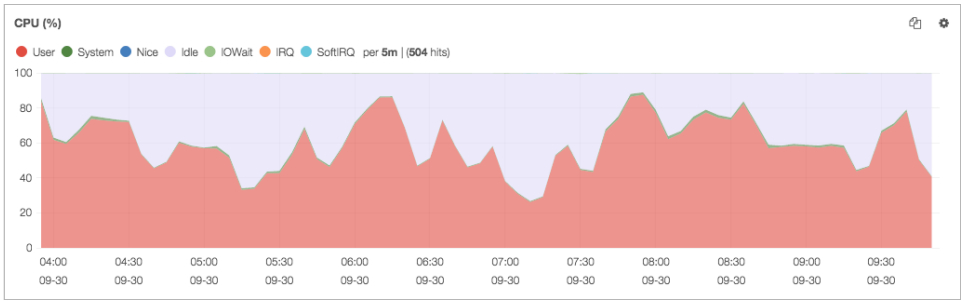
Back to the drawing board!

- Needed to combine optimizations with EPT on
- Huge pages a way out?
  - Idea: reduce the number of pages to be handled, increase hit ratio
- 1GB huge pages
  - Best HS06 results (with EPT on)
  - But: NUMA node distribution uneven when close to hardware limits (kernel memory allocation prevents reservation of contiguous 1GB pages)
- 2MB huge pages
  - Also one of the default sizes
  - Performance loss around 5% compared to bare metal on batch VMs

The “Kilo-1” configuration

- NUMA + Pinning
  - 1-to-1 vs. 1-to-N no difference
- 2MB huge pages
  - 1GB slightly better
- EPT on
  - EPT off still better in HS06

VM sizes (cores)	Before	After
4x 8	7.8%	3.3% (batch WN)
2x 16	16%	4.6% (batch WN)
1x 24	20%	5.0% (batch WN)
1x 32	20.4%	3-6% (bare SLC6 … batch WN)

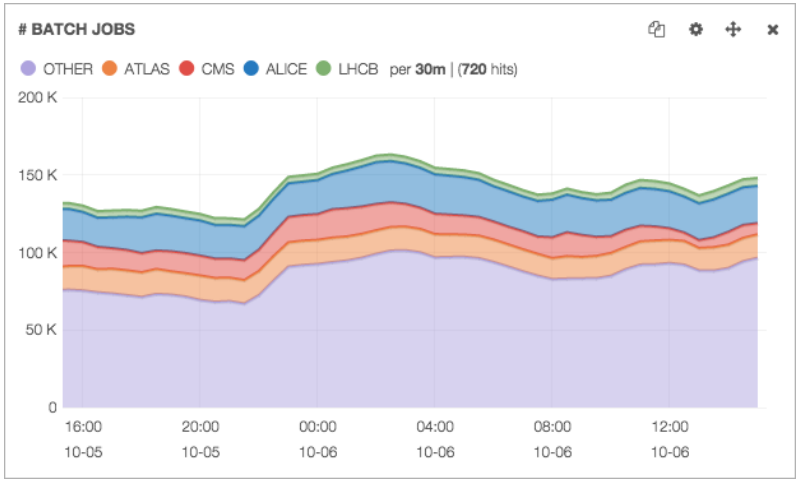


ATLAS T0 host with batch VM running the new config: throughput for recon jobs 20% higher!

OpenStack Kilo will fully support our desired configuration!

Pre-deployment testing

- The first optimizations were of course tested before being rolled out
  - ~30 batch nodes for some weeks
- The slow-job issue was not detected!
  - ATLAS: work load on separate cell
  - LHCb: issue affected “small fraction of a small fraction”
- A small fraction can cause a lot of trouble …



Summary & Conclusion

- We managed to reduce the virtualization HS06 overhead to a few percent compared to bare metal
  - On full node VMs!
  - NUMA + pinning + huge pages + EPT
- Pre-deployment testing difficult
  - EPT side-effects undetected despite weeks of testing
  - Similar issue with KSM and un-reclaimable kernel memory
- Continuous benchmarking needed!
  - See Sean's talk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