Power Monitoring At The NCSA Innovative Systems Lab

Energy-Efficient HPC Working Group Webinar

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NCSA ISL and Others

- Jim Philips and John Stone: Theoretical and Computational Biophysics Group, Beckman Institute, UIUC
- Kenneth Esler: NCSA and UIUC Physics
- Joshi Fullop: NCSA Systems Monitoring
- Jeremy Enos, Volodymyr Kindratenko, Craig Steffen, Guochun Shi, Mike Showerman: NCSA Innovative Systems Laboratory
- Wen-mei Hwu and William Gropp: UIUC ECE Department

Overview

- AC GPU computing cluster
- Power monitoring
    - Search for power monitors
    - Roll our own--version 1: Tweet-A-Watt
    - Roll our own--version 2: Arduino-based power monitor
- Power monitoring on real applications
- EcoG Cluster
- EcoG Top500 and Green500 submissions

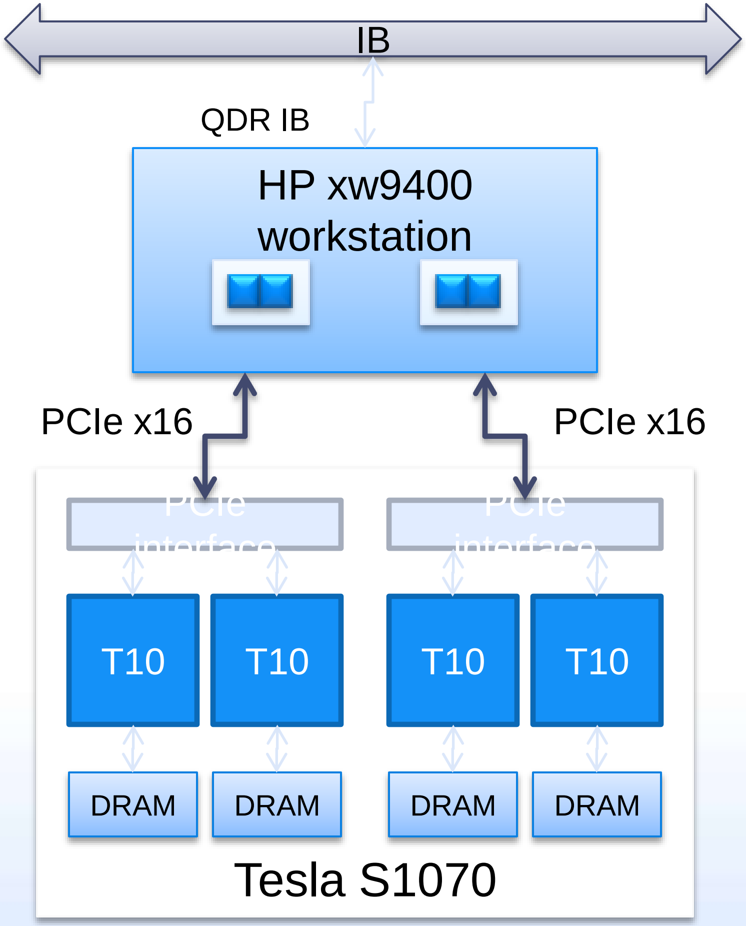
AC cluster (Accelerator Cluster)

- Originally “QP” cluster for “Quadro Plex”
- 32 HP XW9400 nodes. Each node:
  - 2 dual-core 2.4 GHz Opteron 2216
  - 8 GB RAM per node
  - **NVIDIA Tesla S1070 each:**
    - **4 Tesla C1060 GPUs (128 total in cluster)**
- Interconnect network is QDR Infiniband
- CUDA 3.1 compiler/build stack
- Job control/scheduler Moab
  - **Specific resource management for jobs via Torque**
- QP first commissioned November 2007
- AC on-line since December 2008

AC Cluster

AC01-32 nodes

- HP xw9400 workstation
  - 2216 AMD Opteron 2.4 GHz dual socket dual core
  - 8GB DDR2 in ac04-ac32
  - 16GB DDR2 in ac01-03, “bigmem” on qsub line
  - PCI-E 1.0
  - Infiniband QDR
- Tesla S1070 1U GPU Computing Server
  - 1.3 GHz Tesla T10 processors
  - 4x4 GB GDDR3 SDRAM
  - 1 per host



AC cluster used for

- Virtual school for Science and Engineering (attached to the Great Lakes Consortium for Petascale Computing) NVIDIA/CUDA August 2008,2009,2010
- Other classes in 2010:
  - “Intro to CUDA” Volodymyr Kindratenko, Singapore June 13-19
  - Barcelona Spain, Wen-Mei Hwu July 5-9
  - Thomas Scavo July 13-23
  - “Proven Algorithmic Techniques for Many-core Processors” Thomas Scavo August 2-6
  - John Stone August 7-8

AC GPU Cluster Power Measurements

State	Host Peak (Watt)	Tesla Peak (Watt)	Host power factor (pf)	Tesla power factor (pf)
power off	4	10	.19	.31
start-up	310	182		
pre-GPU use idle	173	178	.98	.96
after NVIDIA driver module unload/reload(1)	173	178	.98	.96
after deviceQuery(2) (idle)	173	365	.99	.99
GPU memtest #10 (stress)	269	745	.99	.99
after memtest kill (idle)	172	367	.99	.99
after NVIDIA module unload/reload(3) (idle)	172	367	.99	.99
VMD Madd	268	598	.99	.99
NAMD GPU STMV	321	521	.97-1.0	.85-1.0(4)
NAMD CPU only ApoA1	322	365	.99	.99
NAMD CPU only STMV	324	365	.99	.99

1. Kernel module unload/reload does not increase Tesla power
2. Any access to Tesla (e.g., deviceQuery) results in doubling power consumption after the application exits
3. Note that second kernel module unload/reload cycle does not return Tesla power to normal, only a complete reboot can
4. Power factor stays near one except while load transitions. Range varies with consumption swings

Search for Power Monitors: What questions do we want to answer?

- How much power do jobs use?
- How much do they use for pure CPU jobs vs. GPU-accelerated jobs?
- Do GPUs deliver a hoped-for improvement in power efficiency?

Hardware: Criteria for data-sampling device

- Cheap
- Easy to buy/produce
- Allows access to real data (database or USB, no CD-installed GUIs)
- Monitors 208V 16A power feed
- Scalable solution across machine room (one node can collect one-node's data)

Search for Good (and Cheap) Hardware Power Monitoring

- Laboratory units too expensive
- Commercial Units:
  - 1A granularity?
  - No direct data logging
  - No real-time data logging

Very capable

- **PS3000 PowerSight Power Analyzer**
  $ 2495.00

Capable; Closer but still too expensive

- ElitePro™ Recording Poly-Phase Power Meter Standard Version consists of:
- US/No. America 110V 60 Hz Transformer
- 128Kb Capacity
- Serial Port Communications
- Indoor Use with Crocodile Clips
- Communications Package (Software) and Current Transformers sold separately.
- More Information

  Price: $965.00   Part Number: EP

Instrumented PDUs: poor power granularity

- 1A granularity
- 120V circuits

Watts-up integrated power monitor: CLOSE

- Smart Circuit 20 31298 $194.95
- Outputs data to web page (how to efficiently harvest this data?)

Data Center Power—208 V, 20 or 30A

Power Monitoring Version 1:
Tweet-a-Watt Receiver and Transmitter


http://www.ladyada.net/make/tweetawatt/

Kits available from www.adafruit.com

Tweet-a-Watt

- Kill-a-watt power meter
- Xbee wireless transmitter
- power, voltage, shunt sensing tapped from op amp
- Lower transmit rate to smooth power through large capacitor
- Readout software modified from available Python scripts to upload sample answers to local database
- We built 3 transmitter units and one Xbee receiver
- Currently integrated into AC cluster as power monitor

Evaluation of Tweet-a-Watt

- Limited to Kill-a-Watt capability (120V, 15A circuit)
- Low sampling rate (report every 2 seconds, readout every 30 seconds)
- Either TWO XBEE units required or scaling issue
- Fixed but configurable program; one set, difficult to program (low sampling rate means unit is off most of the time)

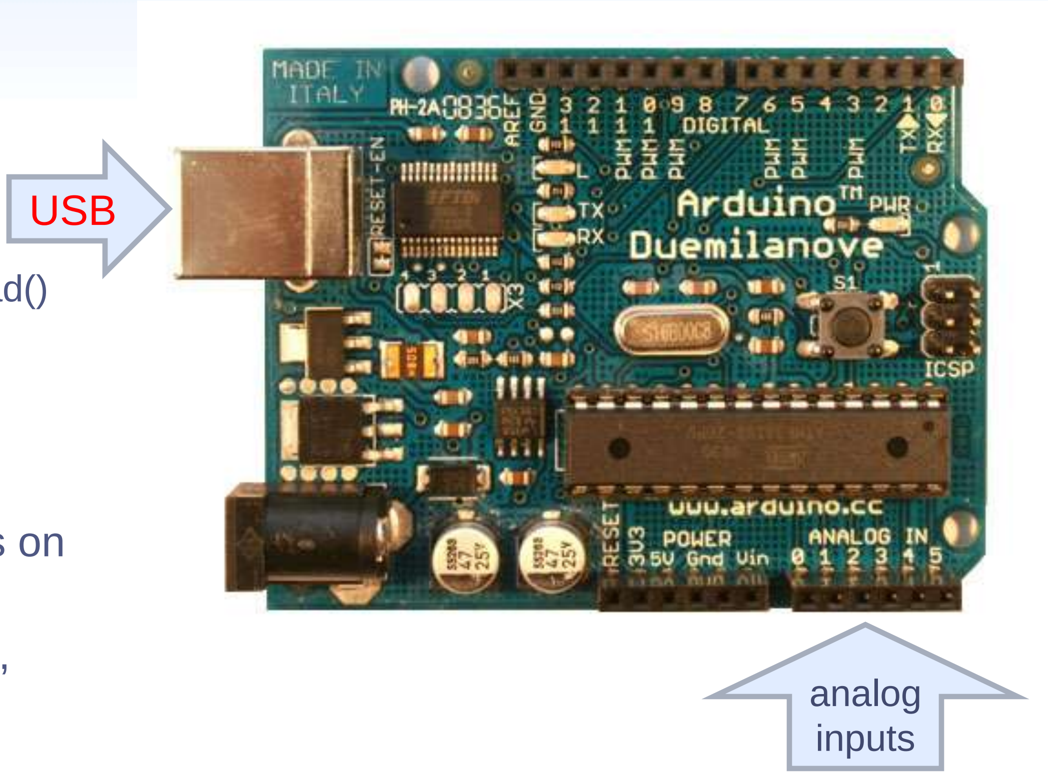
- Correlated voltage and current (read power factor and true power usage)
- 50-foot plus range (through two interior walls)
- Currently tied to software infrastructure: Application power studies done with Tweet-a-Watt

Power Monitor version 2:
One-off function Prototype Power Monitor

- Used chassis from existing (120 V) PDU for interior space
- Connectors, breaker, and wiring to carry 208V 16A power distribution
- Current sense transformers and Arduino microcontroller for current monitoring
- Prototyped (but not deployed) Python script to insert output into power monitor database

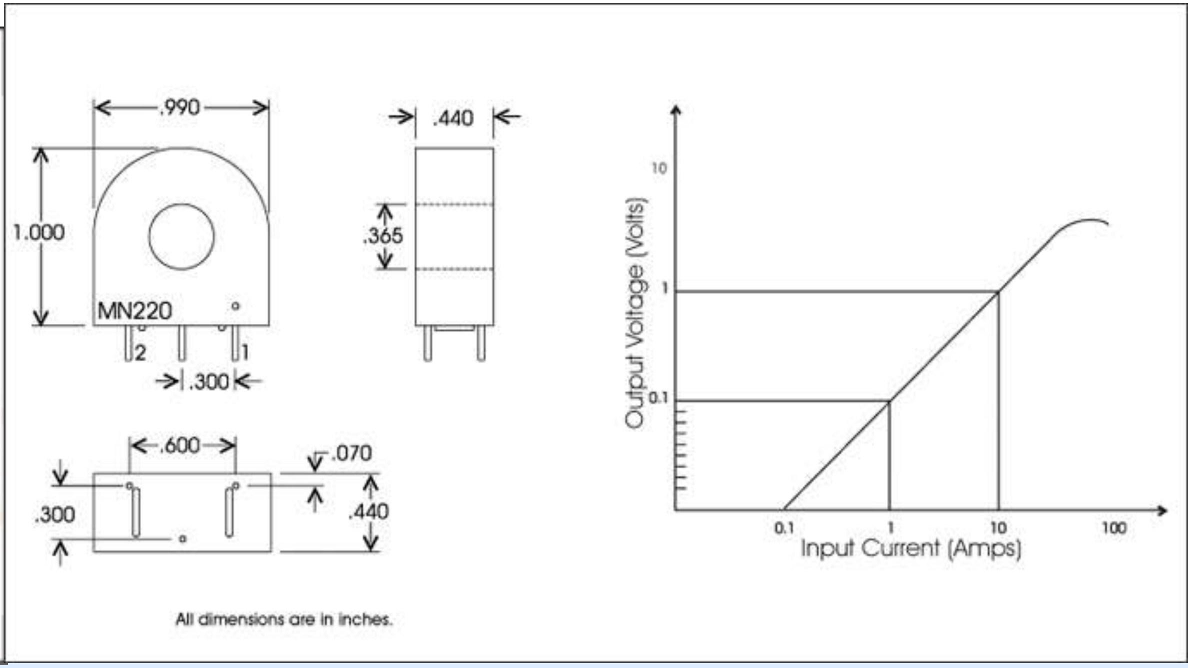
Arduino-based Power Monitor

- Based on Arduino Duemilanove
  - Runs at 16 MHz
  - has 6 analog voltage-to-digital converters (sampled explicitly by read() function)
  - Runs microcode when powered on (from non-volatile memory)
- Accumulates sample arrays for N samples per channel per report (N is on subsequent slides)
- Accumulates current measurements, computes RMS values, and outputs results in ASCII on USB connection
- Arduino is powered from the USB connection



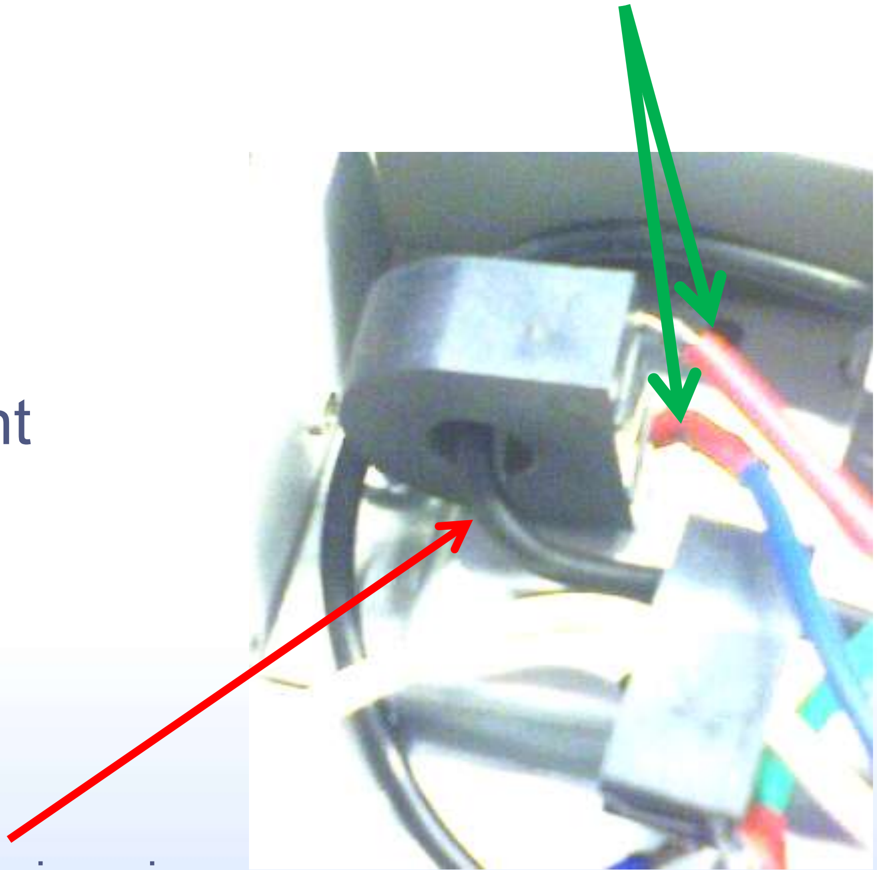
MN 220 picking transformer from Manutech

- Manutech.us
- 1000 to 1 voltage transformer; 1 to 1000 current transformer
- Suggested burden resistor: 100 Ohms.
- AC output voltage proportional to AC current input.
- Output at 100 Ohms: 100 mV/Amp.
- Various ranges of output are achievable by using different burden resistors.



Current Sense Transformer

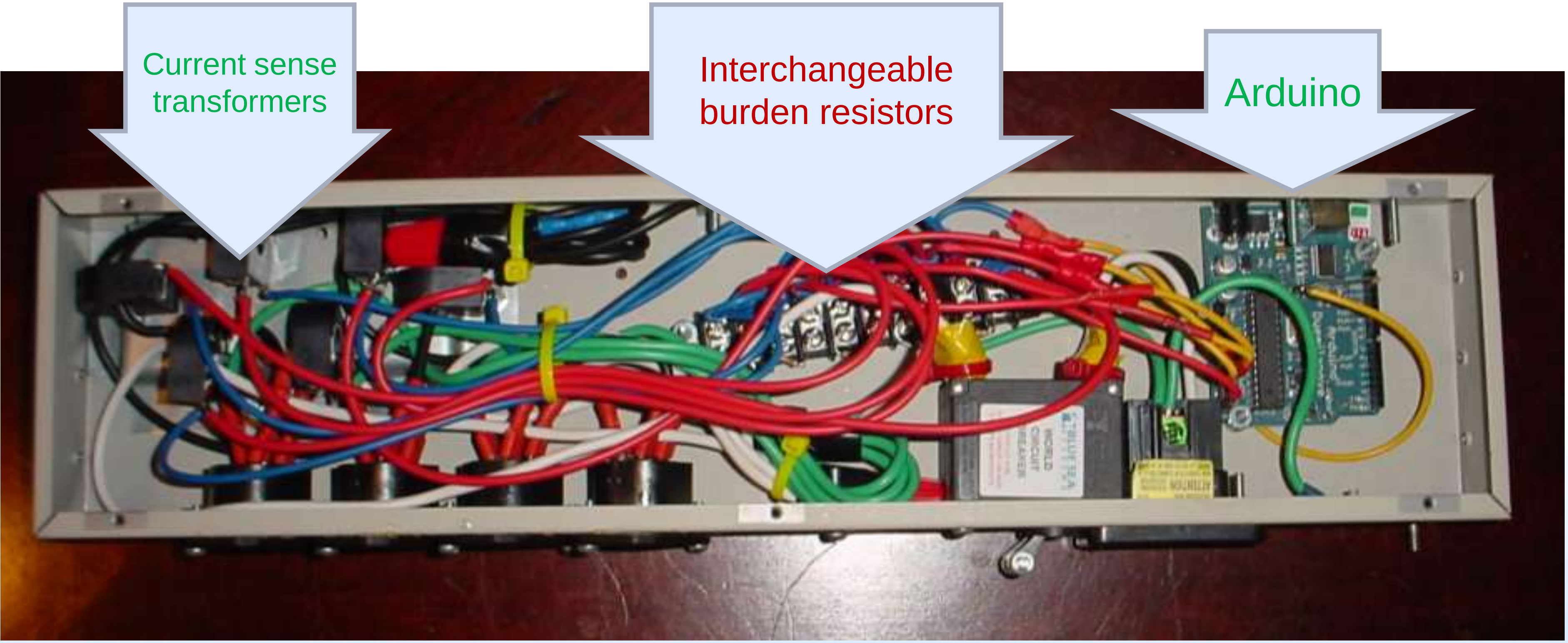
- MN-220 current “transformer” designed for 1 to 20 amp primary
  - 1000-1 step-up current transformer
- Burden resistor sets the sensitivity; sets “volts per count” calibration constant
- Allows current monitoring without Arduino contact with high-voltage wires


Sense wires

AC Current carrying wire

Industrial Design

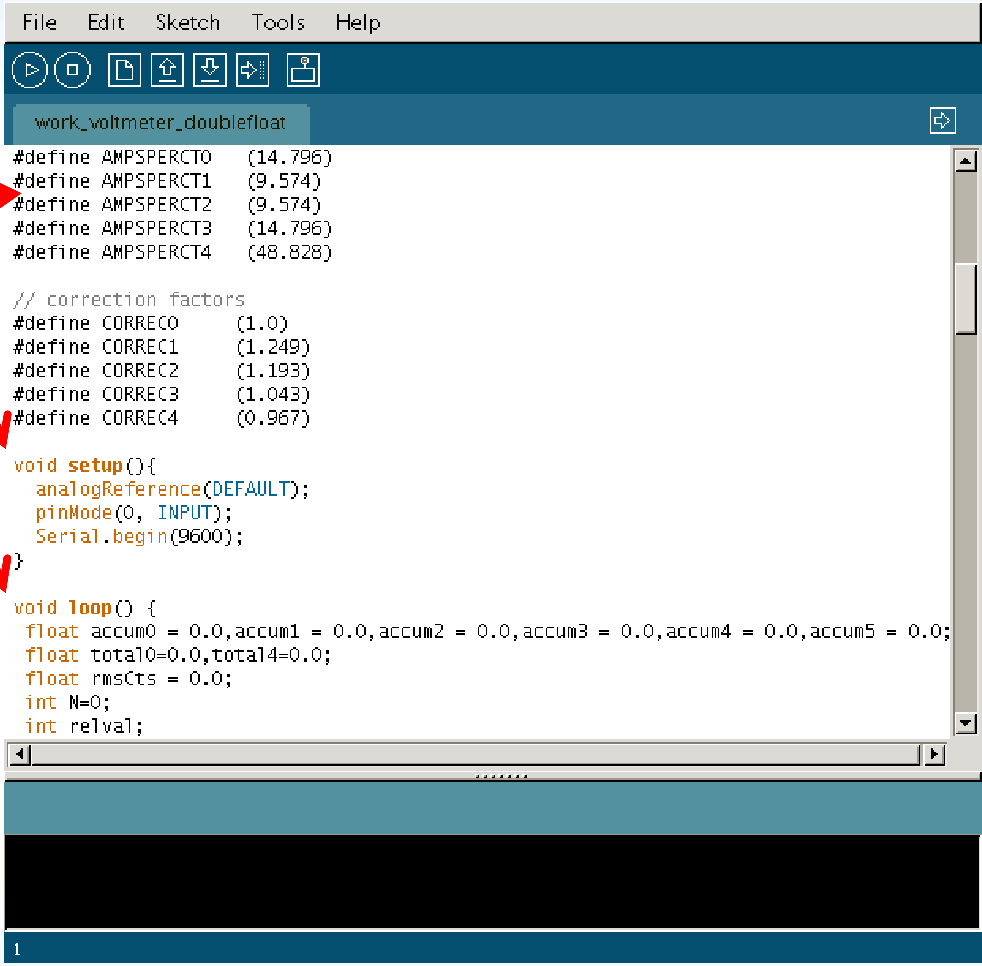
- 5 separate sense transformers for 4 power legs and opposite leg of input
- Current sense ONLY; Arduino is competely isolated from power conductors. No phase or power factor information, RMS current *only*



Arduino development environment

- C-like language environment
  - #defines for calibration constants
  - Initial setup() function runs once
  - loop() function repeats forever

SPECIAL WARNING: Arduino INTs are 16 bits! Summing the squares of measured voltages (in the 200 to 400 range) will OVERFLOW the accumulator INT. (Convert to float b efore squaring)

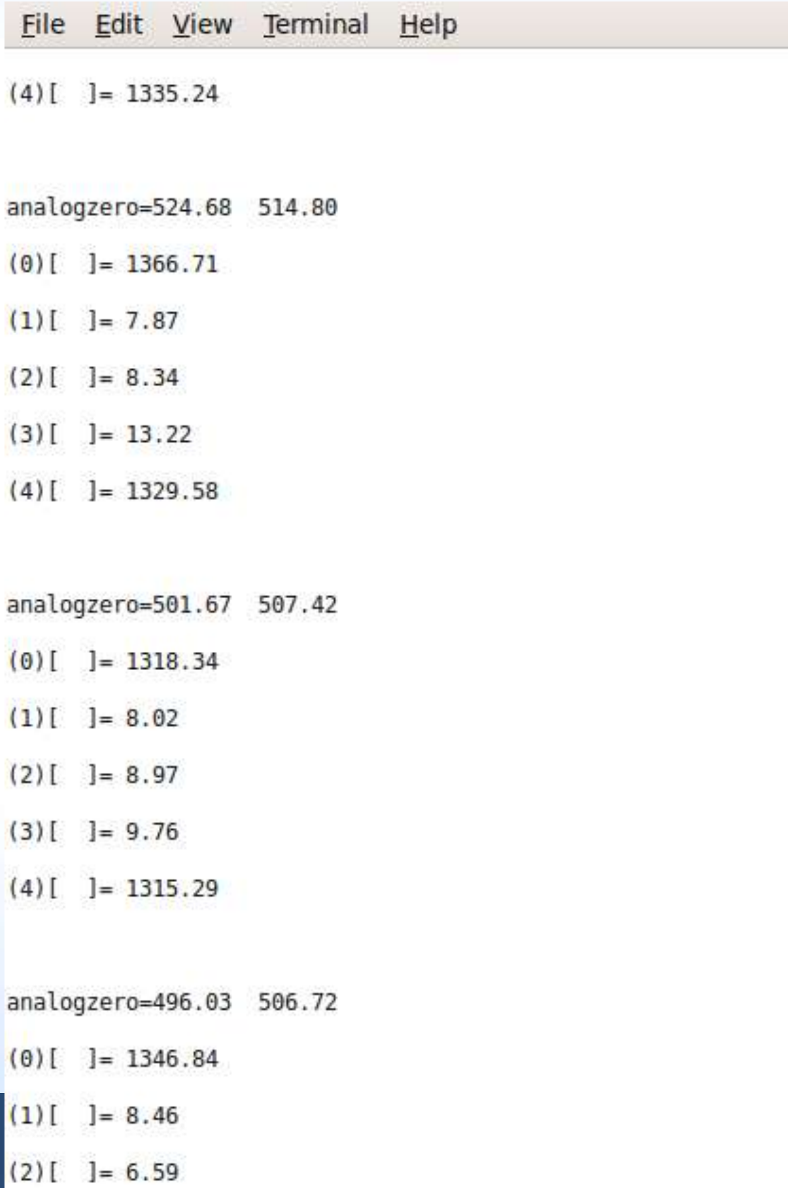


```
#define AMPSPERCT0   (14.796)
#define AMPSPERCT1   (9.574)
#define AMPSPERCT2   (9.574)
#define AMPSPERCT3   (14.796)
#define AMPSPERCT4   (48.828)

// correction factors
#define CORREC0     (1.0)
#define CORREC1     (1.249)
#define CORREC2     (1.193)
#define CORREC3     (1.043)
#define CORREC4     (0.967)

void setup(){
  analogReference(DEFAULT);
  pinMode(0, INPUT);
  Serial.begin(9600);
}

void loop() {
 float accum0 = 0.0,accum1 = 0.0,accum2 = 0.0,accum3 = 0.0,accum4 = 0.0,accum5 = 0.0;
 float total0=0.0,total4=0.0;
 float rmsCts = 0.0;
 int N=0;
 int relval;
```

Output Format (our implementation

- Every sampling period outputs block of ASCII text to virtual console (accessed under Linux typically at /dev/ttyUSB0)
- No protocol or readers necessary; software can be checked with commands *tail* or *more*
- If ANY sample on a channel is within 10% of the hard limit, then the channel is flagged as “overflow” in the output stream

(note the \r \n double-line breaks)



```
(4)[  ]= 1335.24



analogzero=524.68  514.80

(0)[  ]= 1366.71

(1)[  ]= 7.87

(2)[  ]= 8.34

(3)[  ]= 13.22

(4)[  ]= 1329.58



analogzero=501.67  507.42

(0)[  ]= 1318.34

(1)[  ]= 8.02

(2)[  ]= 8.97

(3)[  ]= 9.76

(4)[  ]= 1315.29



analogzero=496.03  506.72

(0)[  ]= 1346.84

(1)[  ]= 8.46

(2)[  ]= 6.59
```

Calibration, Uncertainty and Readout Speed

- Arduino only does RMS summing; not synchronized with AC clock. Possible sampling errors from undersampling AC waveform (hopefully eliminated by enough samples)
- Samples-per-report is set high enough to minimize undersampling errors
- Uncertainty measured with idle node (upper uncertainty limit only)

Measurements per report	Time between reports (s)	Uncertainty (mA)
250	.28	±7
125	.2	±8
60	.15	±35

Industrial design continued

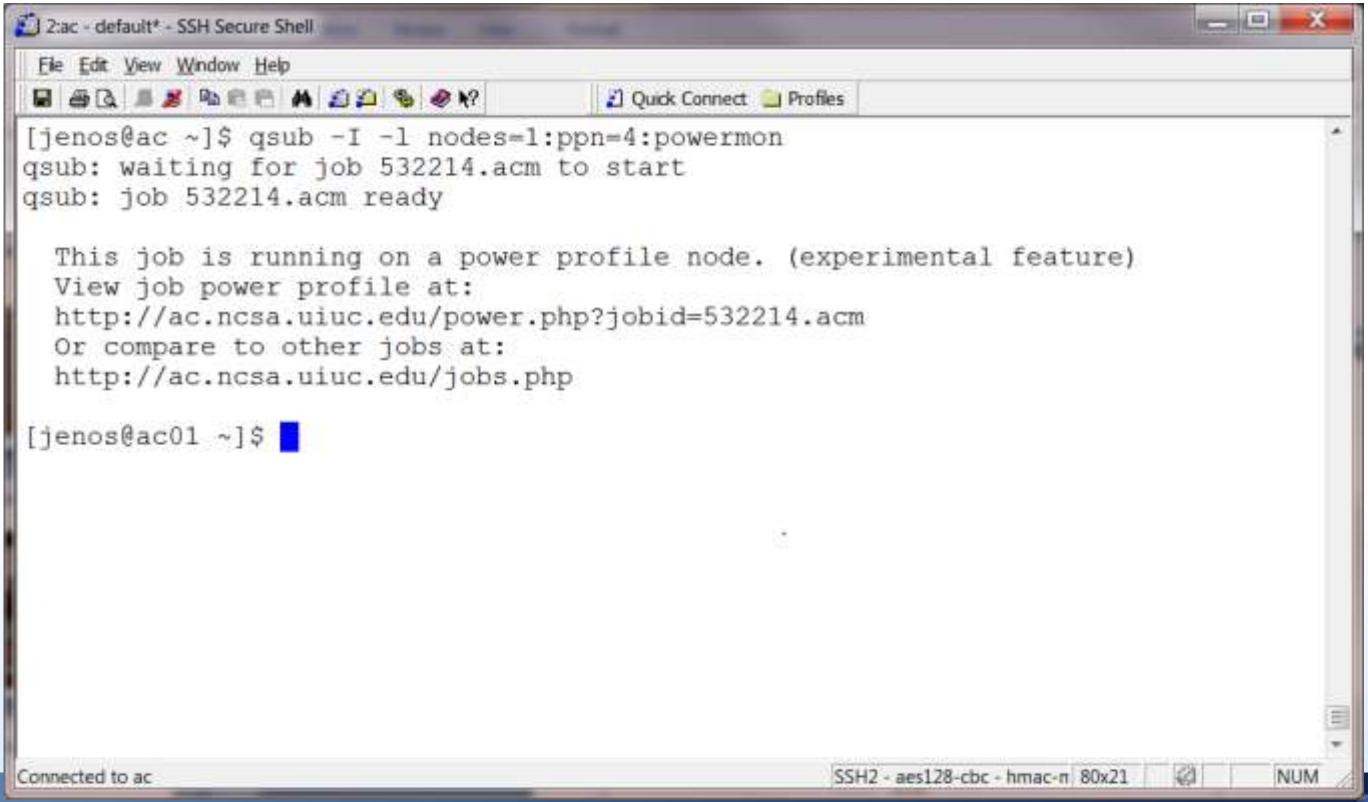
- Interchangable burden resistors to match pickup transformer output voltage to Arduino voltage sense
- Initially configured with two 600W channels, two 1000W channels, and main leg monitor is about 3300W for 16A at 208V
- Conclusion: no advantage to careful matching of burden resistors. Uncertainty of 3300W channel vs. 600W:
  - 250 samples: 6 vs 7mA
  - 125 samples: 8 vs 8
  - 60 samples: 37 vs 35
- Advantage: eliminates a LOT of wiring from the prototype

Data storage and calibration database

- Prolog scripts identify the (one) power monitored node (via Torque)
- Job history entry tags job to be attached to time window of power monitor data
- The job scripts create an automagic link to graphed output data per-sample and total usage summary

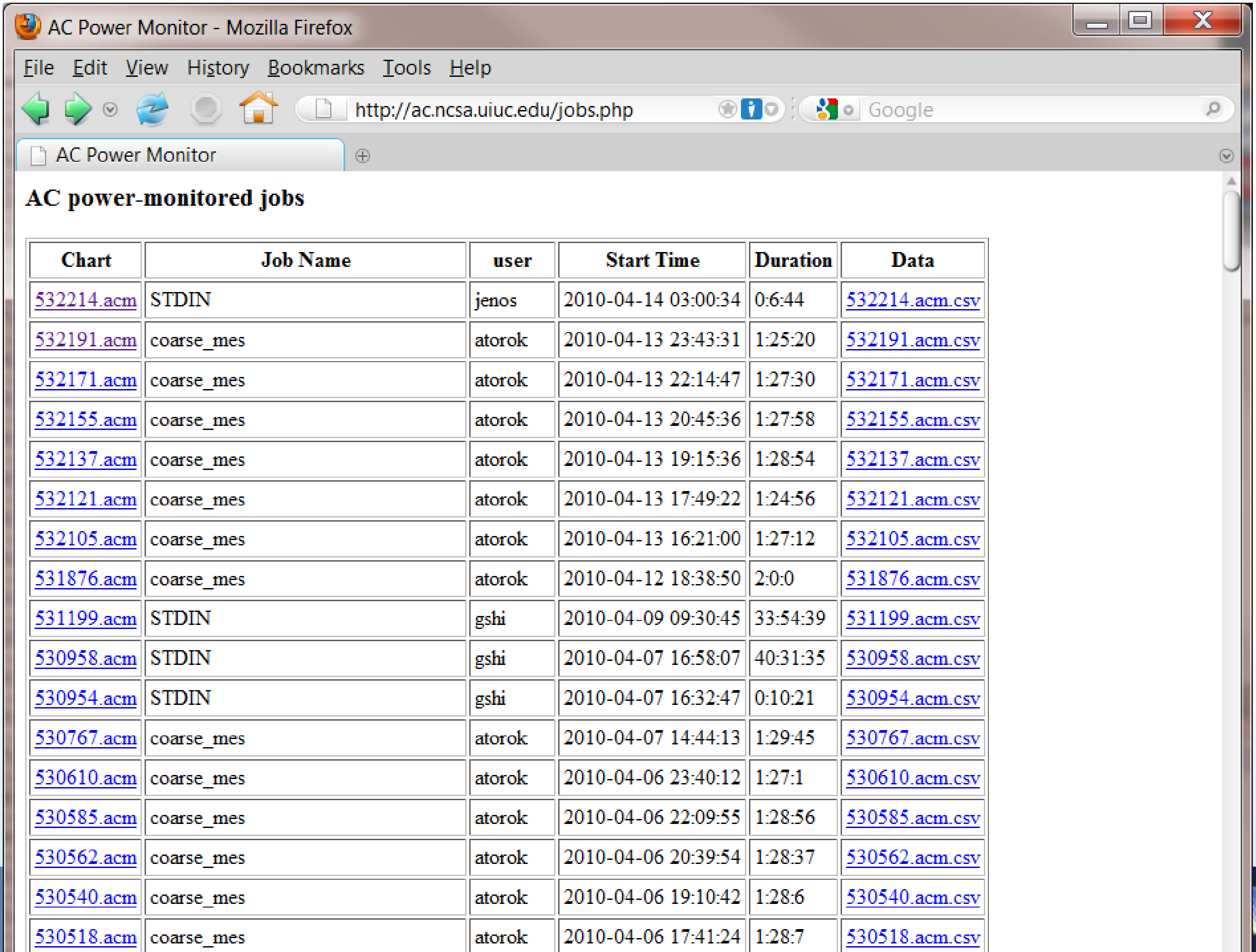
Power monitor data presentation

- http://ac.ncsa.uiuc.edu/docs/power.readme
- submit job with prescribed Torque resource (powermon)
- Run application as usual, follow link(s)



```
[jenos@ac ~]$ qsub -I -l nodes=1:ppn=4:powermon
qsub: waiting for job 532214.acm to start
qsub: job 532214.acm ready

  This job is running on a power profile node. (experimental feature)
  View job power profile at:
  http://ac.ncsa.uiuc.edu/power.php?jobid=532214.acm
  Or compare to other jobs at:
  http://ac.ncsa.uiuc.edu/jobs.php

[jenos@ac01 ~]$
```

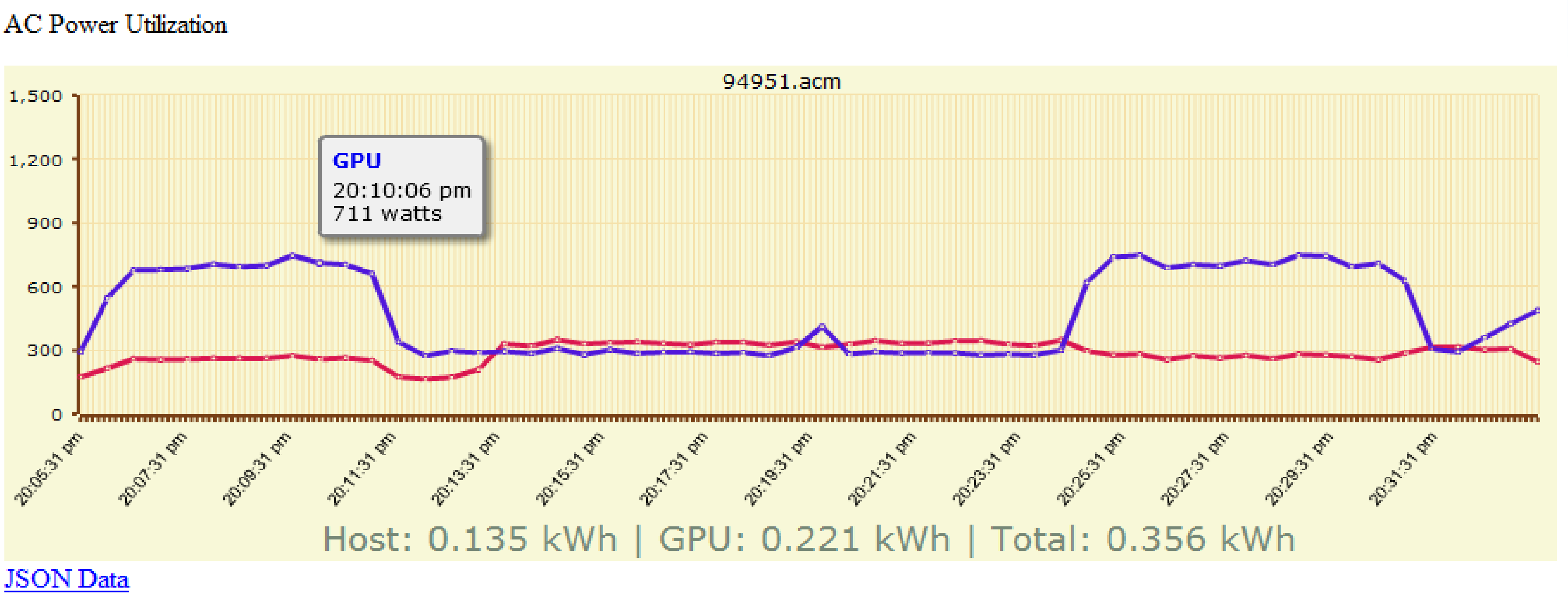
Each monitored job shows up as a link at http://ac.ncsa.uiuc.edu/jobs.php



AC power-monitored jobs

Chart	Job Name	user	Start Time	Duration	Data
532214.acm	STDIN	jenos	2010-04-14 03:00:34	0:6:44	532214.acm.csv
532191.acm	coarse_mes	atorok	2010-04-13 23:43:31	1:25:20	532191.acm.csv
532171.acm	coarse_mes	atorok	2010-04-13 22:14:47	1:27:30	532171.acm.csv
532155.acm	coarse_mes	atorok	2010-04-13 20:45:36	1:27:58	532155.acm.csv
532137.acm	coarse_mes	atorok	2010-04-13 19:15:36	1:28:54	532137.acm.csv
532121.acm	coarse_mes	atorok	2010-04-13 17:49:22	1:24:56	532121.acm.csv
532105.acm	coarse_mes	atorok	2010-04-13 16:21:00	1:27:12	532105.acm.csv
531876.acm	coarse_mes	atorok	2010-04-12 18:38:50	2:0:0	531876.acm.csv
531199.acm	STDIN	gshi	2010-04-09 09:30:45	33:54:39	531199.acm.csv
530958.acm	STDIN	gshi	2010-04-07 16:58:07	40:31:35	530958.acm.csv
530954.acm	STDIN	gshi	2010-04-07 16:32:47	0:10:21	530954.acm.csv
530767.acm	coarse_mes	atorok	2010-04-07 14:44:13	1:29:45	530767.acm.csv
530610.acm	coarse_mes	atorok	2010-04-06 23:40:12	1:27:1	530610.acm.csv
530585.acm	coarse_mes	atorok	2010-04-06 22:09:55	1:28:56	530585.acm.csv
530562.acm	coarse_mes	atorok	2010-04-06 20:39:54	1:28:37	530562.acm.csv
530540.acm	coarse_mes	atorok	2010-04-06 19:10:42	1:28:6	530540.acm.csv
530518.acm	coarse_mes	atorok	2010-04-06 17:41:24	1:28:7	530518.acm.csv

Power Profiling – Walk through



AC Power Utilization

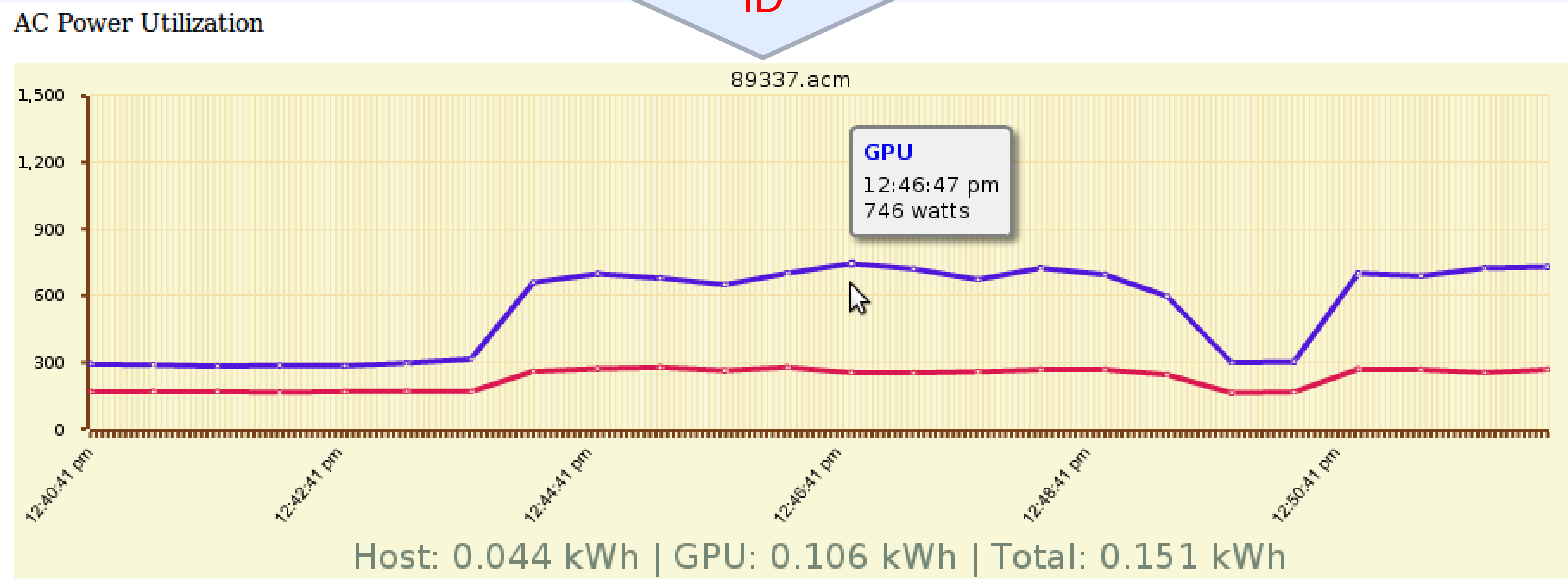
Host: 0.135 kWh | GPU: 0.221 kWh | Total: 0.356 kWh

JSON Data

- Mouse-over value displays
- Under curve totals displayed
- If there is user interest, we may support calls to add custom tags from application

Output Graphs

Job
ID



Host: 0.044 kWh | GPU: 0.106 kWh | Total: 0.151 kWh

Unique Features of this Hardware+Software Setup

- Hardware solution
  - Cheap
  - Scalable
- Presentation integrated with job software
- Simple to use with jobs.php link
- Not required; can be ignored by other users

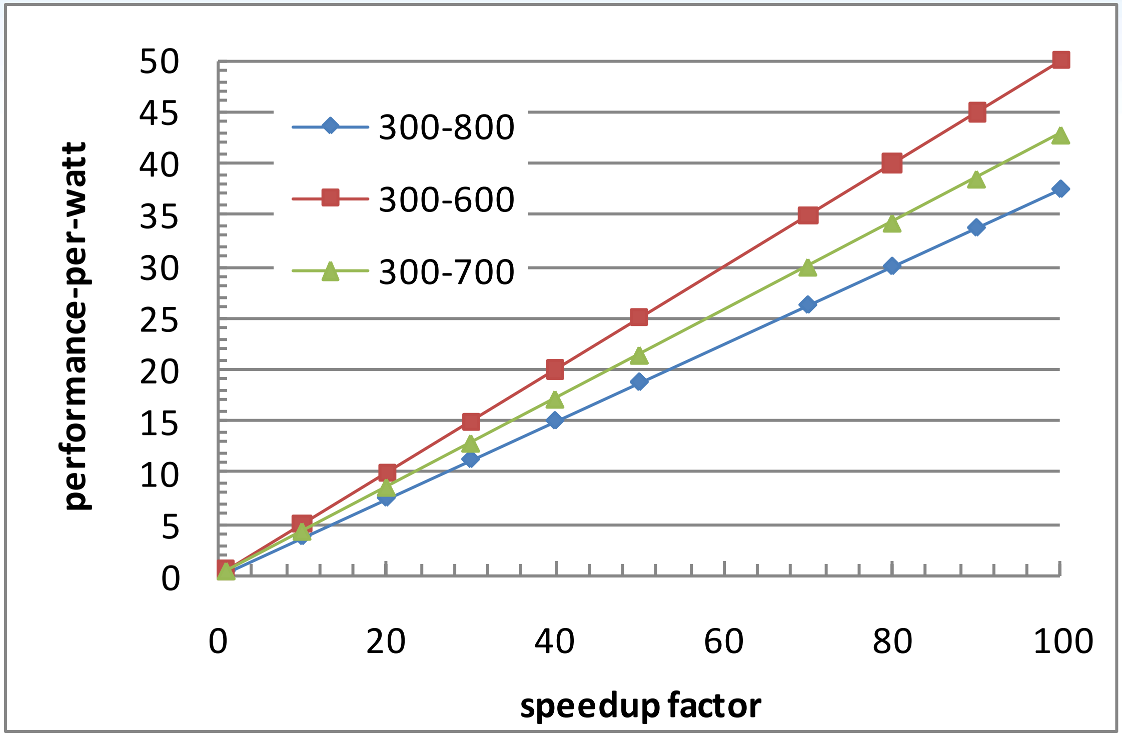
Real Application Speed and Efficiency

- Speedup measured in terms of **wall clock time** for whole application to run
- Power consumption measurements made over at least 20 sample runs
- Removed power measurements from startup and shutdown phases of applications

NOTE: The NVIDIA cards have internal power measuring. We didn't use them because

  - That leaves out the power supply of the Tesla
  - We got inconsistent node-to-node results
  - We wanted to understand the systematics of the data

Current State: Speedup to Efficiency Correlation



- The GPU consumes roughly double the CPU power, so a 3x GPU is require to break even
- Performance-per-watt is asymptotically roughly half speedup factor or less

Real Applications Speedup Summary

- NAMD: raw speedup: 6 speedup-per-watt: 2.8
- VMD: raw: 26x XperW: 10.5
- QMCPack: raw: 62 XperW: 23
- MILC: raw: 20 XperW: 8

SAAHPC 2011

- **Symposium on Application Accelerators in High Performance Computing** 2011
- Covers all accelerators including GPUs, FPGAs, Cell
- Co-hosted by **NCSA**, **University of Illinois** and **University of Tennessee**, Knoxville
- 2011 dates and location not announced (June or July)
- Submissions due in April/May 2011

Current news can be found at: **saahpc.org**

EcoG: Tesla 2050-based Cluster

- 128 Tesla 2050 GPU cards donated by NVIDIA
- Significant parts of infiniband fabric donated by QLogic

- Ethernet cables, power cables, PDUs, recycled from retired NCSA “Mercury” and “Tungsten” systems

- EcoG cluster sits on food service shelves and occupies 18 square feet

System Assembled and Installed by Students

~13 students from UIUC ECE/CS departments in cluster-building independent study

2 graduate students from the chemistry department

Mike Showerman, Jeremy Enos, Luke Scharf, and Craig Steffen from ISL

Sean Treichler from NVIDIA

EcoG Design Goals

- Experiment with low-power, high performance GPU-based architecture
- Maps to GPU math capabilities
- Frequent but not constant node-to-node updates
- Likely target apps:
  - Molecular dynamics
  - Fluid dynamics
  - HPL works passably well
- High-performance GPUs, lower power CPUs
- RAM (which also consumes power) just bigger than GPU
- NFS root file system (no hard drive on nodes)

EcoG Final Configuration

- Tesla 2050 GPUs primary computing element; single modest CPU per node
- Single-socket motherboard
- Each node:
  - Intel® Core i3 2.93 GHz CPU
  - 4 GB RAM main memory
  - 1 two-port QDR infiniband card

HPL Function Division

- Intel CPU:
  - main application loop
  - panel factorization
  - DTRSM update
  - final triangular solve
  - residual check
- Tesla GPU:
  - Update DGEMM
  - Rowswap scatter/gather

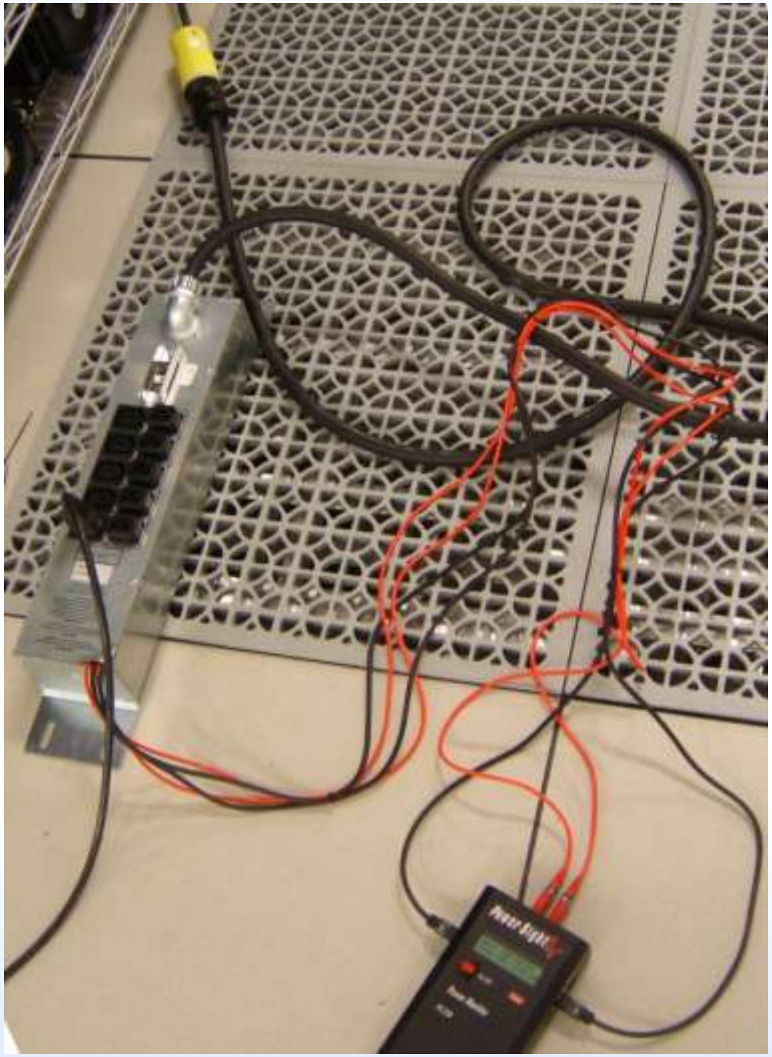
Power Monitoring Setup: Voltage and Current Probes

Re-used rack-mounted PDU

- 2 voltage probes for 208V power legs
- 2 clamp-on current probes for current measurement
- Probes secured INSIDE enclosure

Final Power Monitoring Setup: Enclosed for Convenience and Safety

- L6-30 208V 30A input
- Voltage and current instrumented PDU
- 2 outputs each for 4 cluster nodes
- Powersight voltage/current monitor external



PowerSight power monitor

- Records sampled data to internal memory
- Time-stamped data read out later via serial

Power Data File

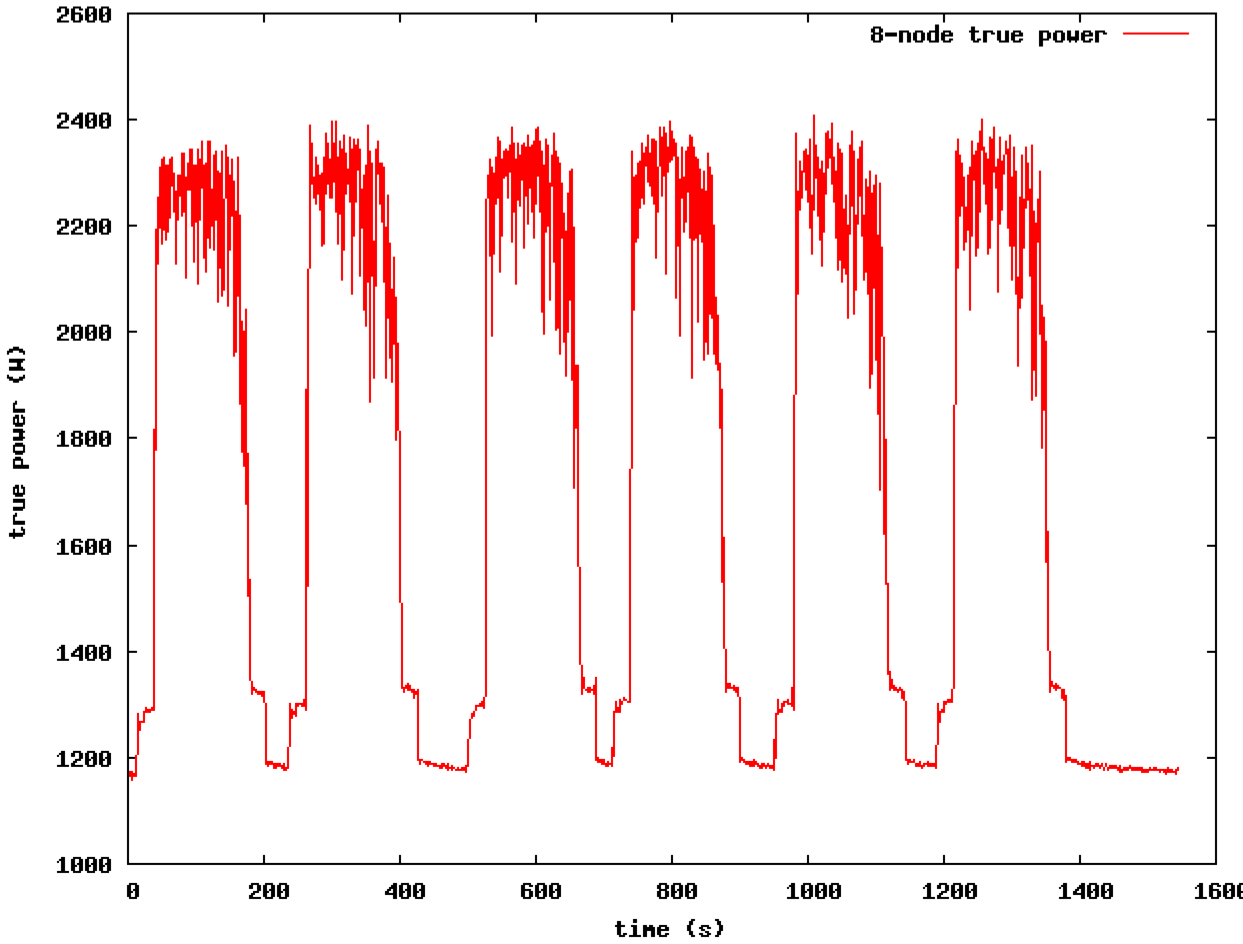
- *
- * Batch Log Began   11/02/10 at 14:16:51
- *
- * Data Type : 0x52 phase-phase
- * Data Period : 62500
- * Data Frames : 1545
- * Mon Period : 1
- * FreqMode   : 2
- * Date Format : 1
- * Log Type   : 1
- * Software Version : 3.3R
- * Firmware Version : 2.a5
- * Hardware Version : 6.00
- * Serial Number   : 25663

Power Data File

- * Start Start V12 V23 V31 I1 I2 I3 In W1 W2 W3 Wt VA1 VA2 VA3 VAt
- * Date Time Avg Avg Avg Avg Avg Avg Avg Avg Avg Avg Avg Avg Avg Avg Avg
- 11/02/10 14:16:51 208.3 100.7 107.2 5.767 5.804 0.000 0.000 603.8 568.2 0.0 1172.0 620.5 584.8 0.0 1204.8
- 11/02/10 14:16:52 208.2 100.9 107.3 5.759 5.819 0.000 0.000 601.0 570.6 0.0 1171.2 617.8 587.5 0.0 1204.8
- 11/02/10 14:16:53 208.5 100.8 107.3 5.767 5.815 0.000 0.000 604.2 569.6 0.0 1173.6 621.0 586.4 0.0 1207.2
- 11/02/10 14:16:54 208.1 100.9 107.3 5.704 5.797 0.000 0.000 596.2 568.5 0.0 1164.0 611.6 585.3 0.0 1196.8

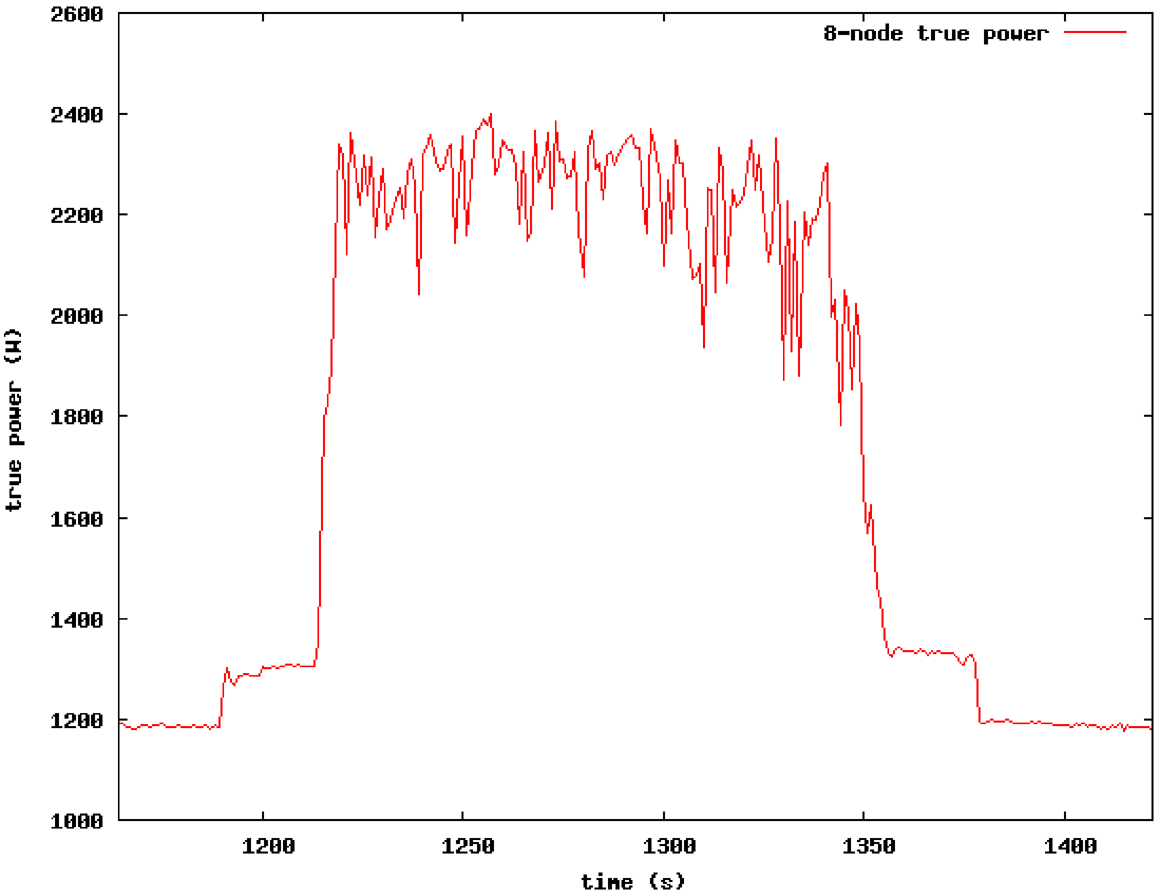
Overall Green500 Entry Test Period (6 HPL Runs)

- 6 HPL runs to get closest match to top500 run and allow for warm-up
- Last (#6) run closest to top500 submission speed



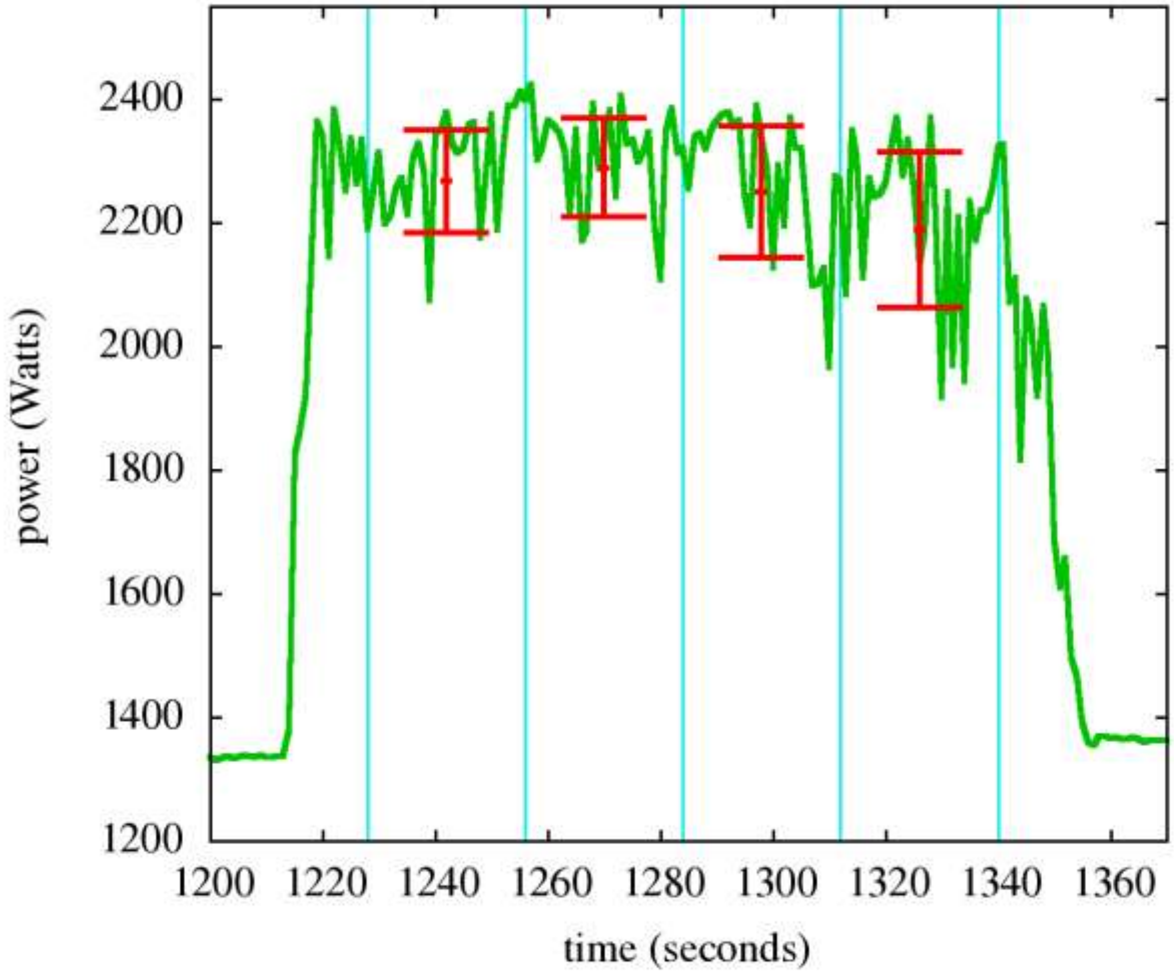
Power Graph for Measured Single HPL Run

- 2 shoulders: front porch for setup, back porch for answer validation
- Features:
    - Negative spikes
    - Power drops slightly over run



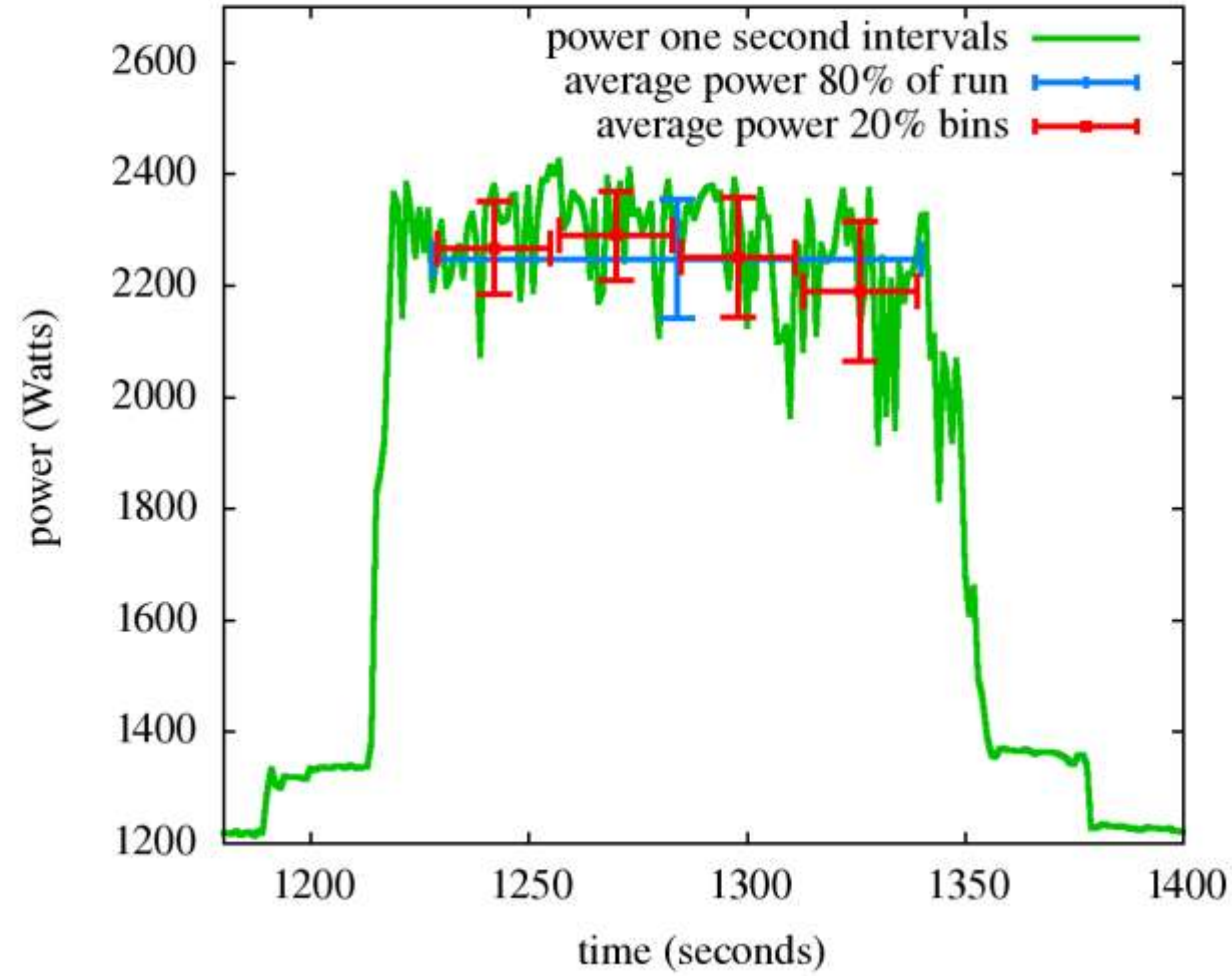
Average 8-node Power Draw In 20% Bins

- Spec for green500 is average power over 20% of run or more
- 4 20% bins in run middle: average 8-node power varies from 2289 W to 2189 W
- Power lowering is real physical effect; GPUS start to run out of computations to do



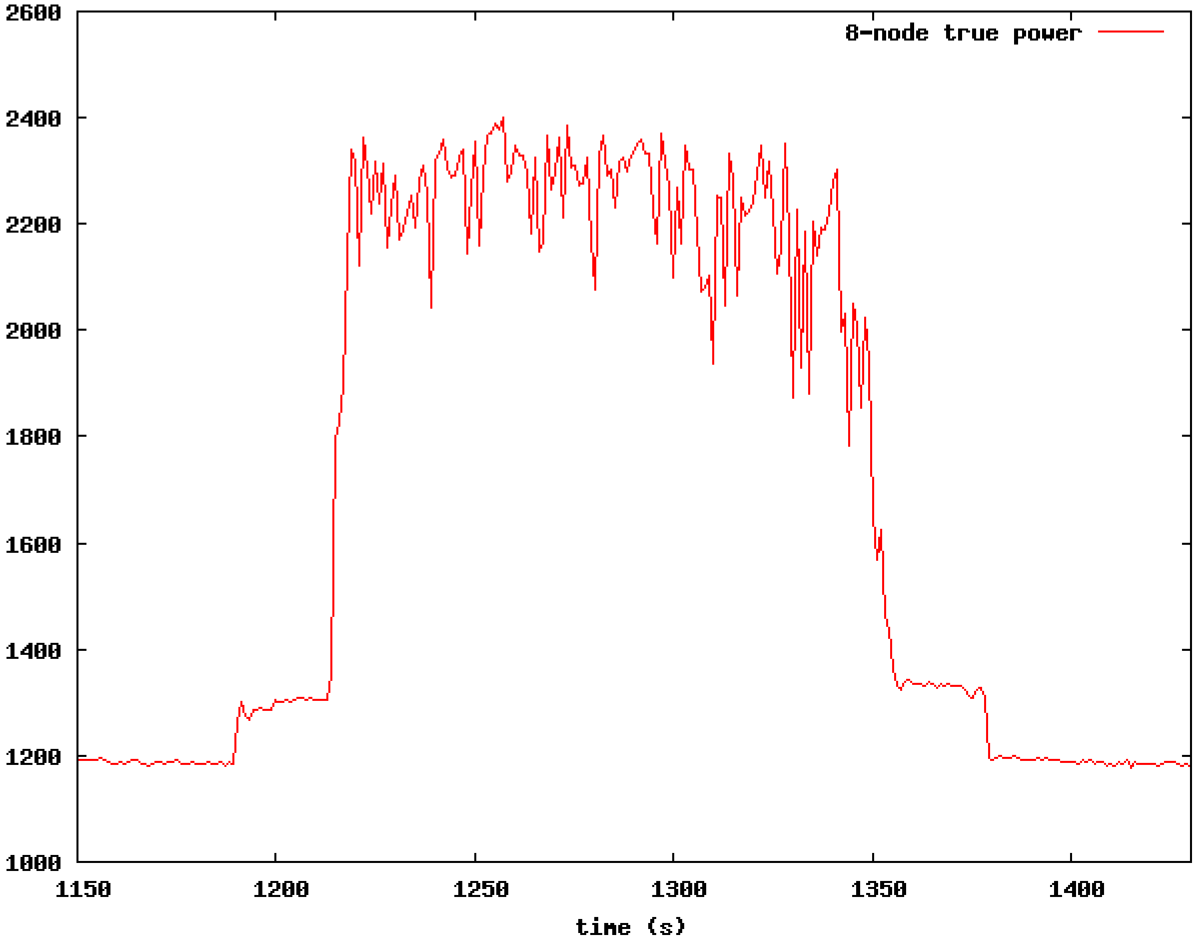
Final Average Power Calculation

- Average power calculated over 10%-90% range
- Calculated to be 2248 W (8 nodes) = 35.97 kW for cluster



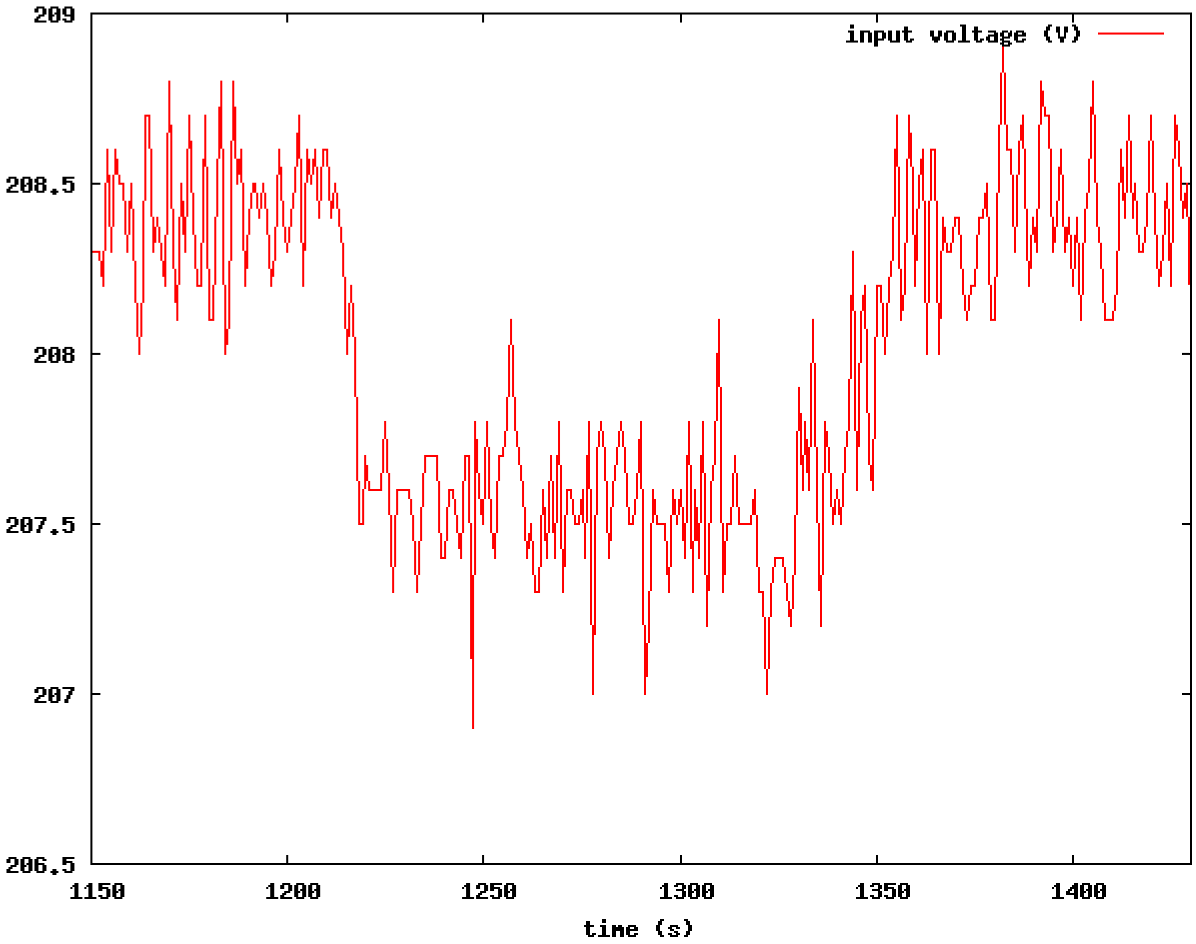
Power Draw for Voltage and Power Factor

- Expanded time range



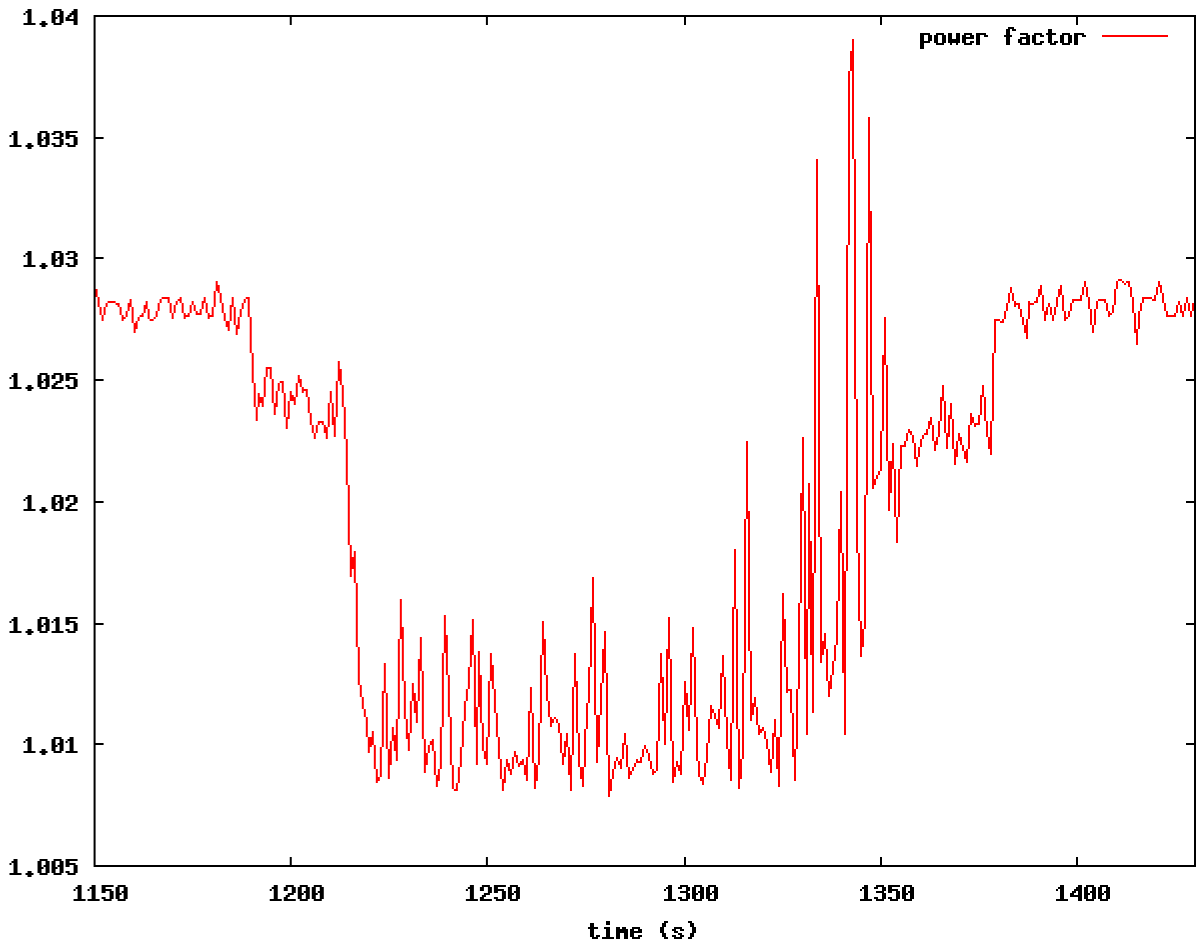
Input Voltage During HPL Runs

- Voltage drops but remains within spec
- Shown here for validation and as a sanity check
- Remains about 207.5 during HPL run



Power Factor

- Power factor remains below 1.035 for whole run including idle time
- Efficient power supplies, not overspecified



Current Questions and Next Steps

- What are the downward power spikes?
    - 1 second resolution *too coarse* to resolve cleanly
    - Need to use .2 second resolution current meter
- What are similar results with 1, 2, 4 nodes?
- How do the high-resolution timing results vary with application phase and input parameters? (Memory saturation tests have smooth graphs.)

- For more info see: http://www.ncsa.illinois.edu/News/Stories/GreenGPU/

Next Steps to Work On:

- High-resolution Application Testing
- Arduino-based power monitor integrated into cluster control
- Instantaneous power available to running application; application control of power monitoring granularity