# Oxford/PTC i404 Current Integrator Performance Report

J. Keister, D. Chabot
BSA/BNL
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to be delivered to:

- Oxford and PTC marketing, sales, and technical staff
- Interested and invested personnel at BNL

## Application.

Synchrotron beamlines performing spectroscopy and radiometry rely upon accurate low current measurements. In addition, all beamline utilize current measurements for beam intensity and positioning diagnostics.

The i404 is presently used to measure low current from photodiodes at synchrotron NSLS/NSLS-II as part of alignment and intensity diagnostics. We would also like to use it to measure ion chambers and other similar devices. Signal levels are typically in the pA to µA range. Accuracy to 0.05 pA (5% at minimum range) is required, for integration times up to 1 second. Additional applications may desire extending the current range to as high as 1 A and speed up to 1 kHz.

For positioning monitoring applications 2 or 4 channels can use a common range although in general the device is most useful with the gain selectable independently among the different channels. Multiple intensity monitors can be supported by one device in this case.

The i404 can be considered an alternative to current amplifier / V-to-F / counter arrangement, picoammeter with remote readout, or generic current ADC.

Two possible usage modes can be envisaged:

1. Continuous integration, with readback on demand via RS232 polling or frequency counting. This method is subject to delay when long integration times are used. Polling is typically limited to 10 Hz bandwidth, so faster data rates will require onboard waveform buffering. Buffered readback of all integrations is required for fly scanning (binning of integration data according to continuously changing scan parameter). I to V or I to F conversion can be useful for interface to other readout devices if onboard readout is not sufficient. However, speed and accuracy performance of the voltage and frequency monitors was not tested for this report.

2. Integration on demand via RS232 trigger.  This method has not been exhaustively explored. However, it can considered to be a clean way of delivering current readback for static (step-and-count scanning mode) state between scan steps (integration start on move complete and move start on integration complete).


Fig. 1.  Photo of i404 as received.

## Interface.

In general, ethernet interface is preferred.  The provided RS232/485 interface is an adequate fallback serial interface.  The communication cable provided, however, is a bit strange for us; RJ45 would have been preferable.

Communication protocols and command sets are in general well documented in the user manual, with a few exceptions.

**Protocol Notes.**

- Assymetric Protocol - device generates a "CR LF" termination for each output to host, while requiring only a LF for commands from host
- No capability to cancel echoing of commands back to host (needlessly complicates parsing)
- Sends LF after echoed command. Nice if a human is parsing the response, otherwise problematic
- Password protected commands/queries are extremely inconvenient

For controls at NSLS-II, EPICS is used (http://www.aps.anl.gov/epics/). Oxford-provided epics software was incomplete and therefore considerable work was necessary to be undertaken to support the required interface via RS232 (work in progress). We can make the software available publicly if there is reasonable demand to do so.

**Software Changes.**

- Autosave/restore machinery missing. Added.
- Fixed StreamDevice protocol file errors (get/setCap,Range,Mode,Err)
- Fixed incorrect string parsing
- Changed initial mode from "Quadrant" (mode 2) to "None" (mode 1)
- Added Asyn Record for general-purpose communication with the device
- Added interface to Integration Time and Current-to-Frequency mapping
- Added simplified EDM panel to access basic current-sensing functionality
- Fixed one of HV-functionality accessors (others are broken)
- Enhanced database processing chains and metadata (EGU,DESC,etc)
- Added interface for Resolution (bits [16-20]) and Line-Frequency Suppression
- Added accessor to Identification string (SCPI *IDN)
- Made more processing chain modifications (grouping of related accesses), and marking key records for processing upon DB initialization
- Removed VDCT noise
- Made significant re-working of device reset functionality. See "$(P):Reset:Seq" for the start of the processing chain. Altered OPI representation of same.

For the current epics database, the following EDM user interface is provided with the following:

Set values:

- Current range
- Resolution (normally set to 20 after range setting)
- Line frequency (not used due to password requirement)
- Number of samples used for averaging (not used)
- Current scaling factor (useful for scaling to photons per second or watts, or changing sign)
- Poll frequency (epics scan rate)
- Monitor and frequency mode
- Reset (initialization sequence performs reset and auto-recalibration)

Readback values:

- Error data
- Serial number
- Integration time
- Capacitance
- Resolution
- Suppression frequency
- Current
- Scaled current
- Averaged current (not used)

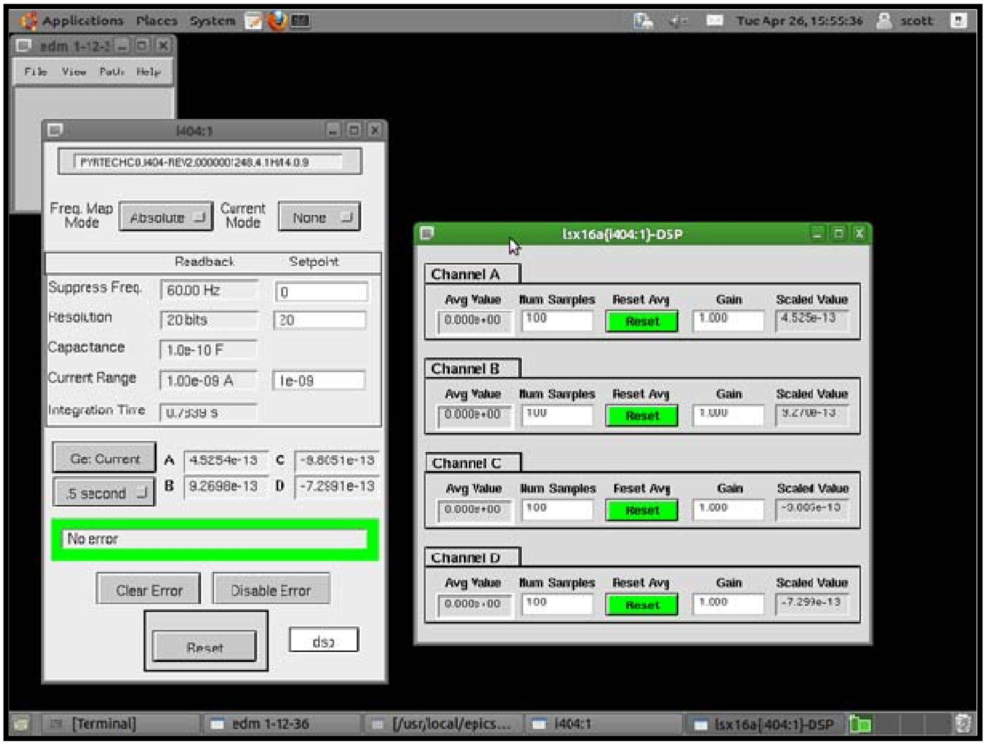

Fig. 2. EDM panels for modified i404 epics database.

We are happy to consult with Oxford/Cosylab and PTC further on the software aspects of this device as desired.

## Tests performed.

(Results in figures and tables below)
Device internally calibrated and tested against a calibrated Keithley 263 current source.

1. Noise performance at longest tolerable integration time (low current range).
   Range of 1E-9 A was used, with “resolution” of 20 bits.  Integration time of 0.8 seconds with polling at 0.2 second was recorded at 1 second per point for 1000 seconds.  Calibrated Keithley 263 current source provided nominal 3 pA input.  Average and standard deviation of recorded values were 3.349 and of 0.055 pA, respectively.  Three-sigma (99.7% confidence) error was therefore 0.165 pA, or 4.93%.
   - ⇨ We would like to see around 10x lower noise for this integration time.  A 10 pA signal should be measurable to within 0.1% (10 fA) within 1 second.
   - ⇨ Source of 0.349 pA offset is not known.
2. Accuracy and noise performance between ranges (constant input).
   1 nA signal input, 20 bit selected for all ranges.  Polling at 1 second, standard deviation was calculated for 5 and 10 adjacent points.  Across all ranges, relative standard deviation was a

relatively constant 3E-5 (equivalent to 15 bit). 3 sigma noise level 0.01%, equivalent to 13 bit. Absolute accuracy within 3 pA, can be improved.

⇨ Would like to see true 16+ bit noise (precision) performance at 3 sigma.

⇨ Accuracy appears to be within 3 pA (1.5% at 2 nA range), somewhat consistent with result of Test 1. Accuracy of 16 bit at all ranges is desired.

3. Linearity and noise performance of single range (variable input).
   200 µA range set, 20 bit resolution (3.3E-9 F capacitor automatically selected). Average and standard deviation are measured for a range of input currents, 50 points for each. Polling at 1 second.

   ⇨ 1-sigma noise (standard deviation) near 15 bit limit as observed previously.

   ⇨ Accuracy varies, ranging from near 18 bit for low signals per range matching to less than 10 bits for signals comprising 10-100% of the selected range. This suggests absolute current accuracy of 0.13%; 16 bit desired (0.0015%).

4. Stability; running stability overnight.
   10 pA current provided by current source, range set to 2E-9 A / 20 bit. Over the course of 12 hours several scans of 200 points each were collected (1 per second).

   ⇨ Drift of ~50 fA per day was observed, this is fully acceptable, and similar to standard deviation of the values from each scan.

   ⇨ Absolute value was accurate to 10 bits (could be better), noise and drift within 15 bits.

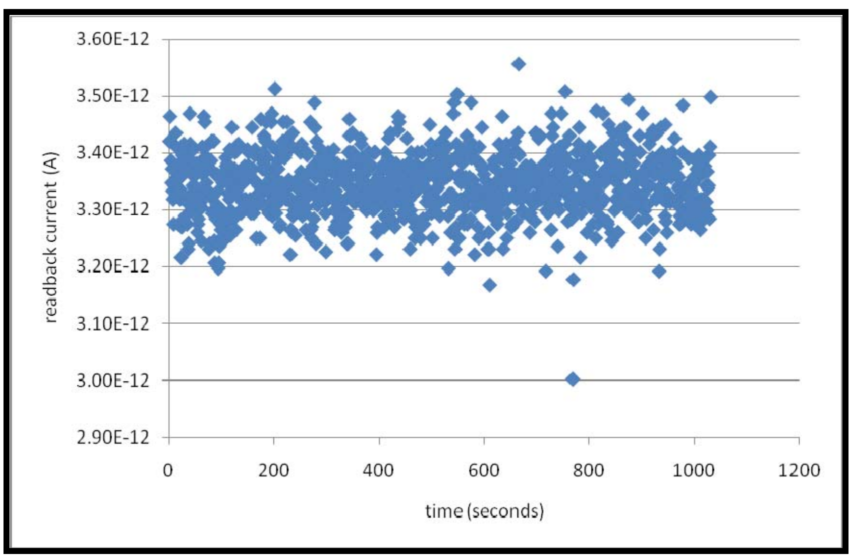


Fig. 3. Test 1 (0.8 sec integration time / 20 bit measurement of 3 pA signal)

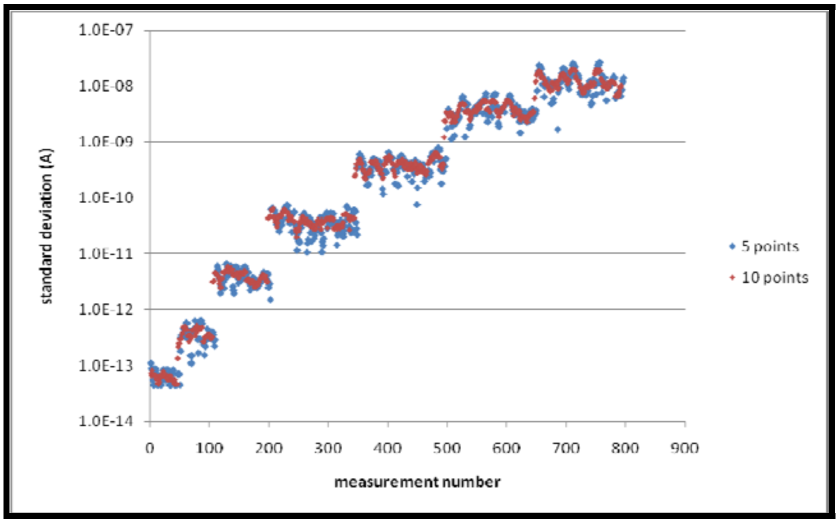


Fig. 4. Test 2(a) (stdev of 20 bit measurement of 1 nA signal, various ranges)

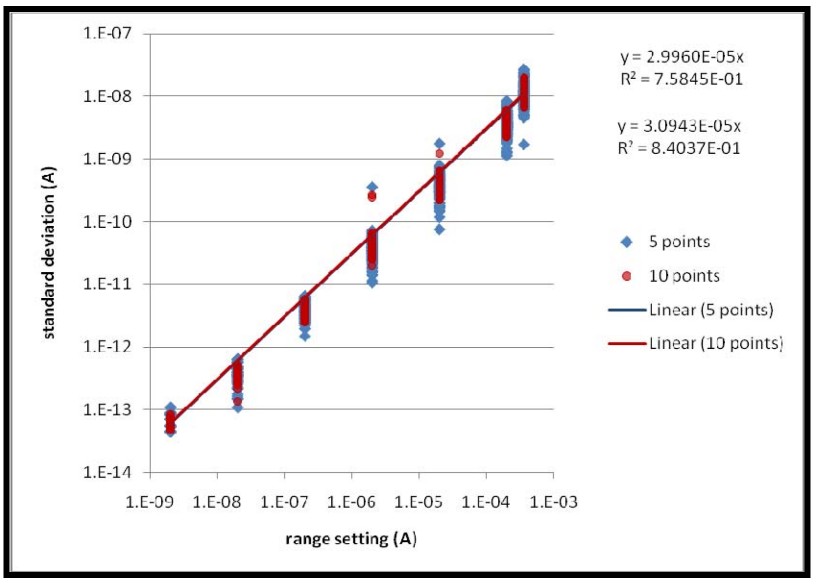


Fig. 5. Test 2(b) (stdev of 20 bit measurement of 1 nA signal, various ranges)

Table I. Data from Test 2. Errors are absolute difference for accuracy and 1-sigma for noise.

| range (A) | average (A) | standard deviation (stdev) (A) | accuracy error per range | bits error (accuracy) | noise (stdev) per range | bits error (noise) |
|---|---|---|---|---|---|---|
| 2.0E-09 | 1.00278E-09 | 7.02397E-14 | 0.1391% | 9.5 | 0.0035% | 14.8 |
| 2.0E-08 | 1.00275E-09 | 4.01444E-13 | 0.0137% | 12.8 | 0.0020% | 15.6 |
| 2.0E-07 | 9.99515E-10 | 4.23431E-12 | 0.0002% | 18.7 | 0.0021% | 15.5 |
| 2.0E-06 | 9.91163E-10 | 8.44260E-11 | 0.0004% | 17.8 | 0.0042% | 14.5 |
| 2.0E-05 | 8.84807E-10 | 5.03656E-10 | 0.0006% | 17.4 | 0.0025% | 15.3 |
| 2.0E-04 | 3.38622E-10 | 4.20650E-09 | 0.0003% | 18.2 | 0.0021% | 15.5 |
| 3.6E-04 | 2.04019E-09 | 1.30589E-08 | 0.0003% | 18.4 | 0.0036% | 14.8 |

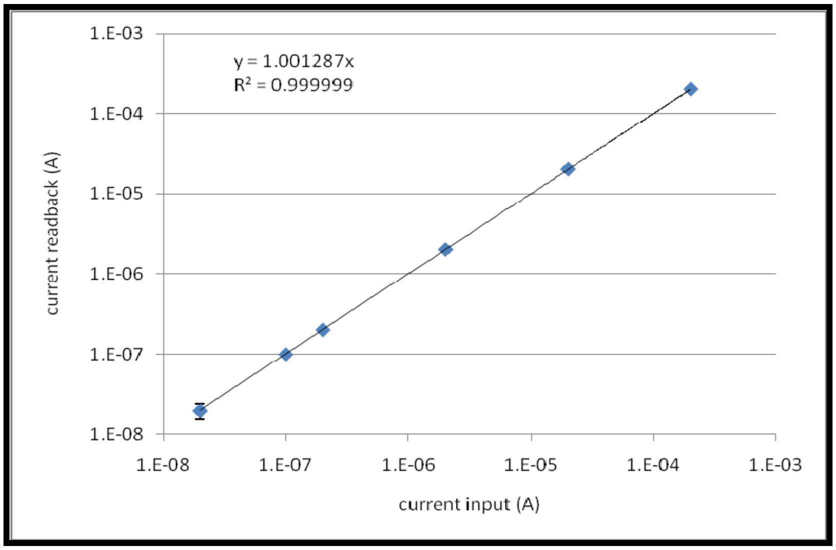


Fig. 6. Test 3 (200 µA / 20 bit range, various inputs)

Table II. Data from Test 3. Errors are absolute difference for accuracy and 1-sigma for noise.

| input (A) | readback (A) | standard deviation (stdev) (A) | accuracy error per range | bits error (accuracy) | noise (stdev) per range | bits error (noise) |
|---|---|---|---|---|---|---|
| 2.0E-08 | 1.9693E-08 | 4.44E-09 | 0.0002% | 19.3 | 0.0022% | 15.5 |
| 1.0E-07 | 9.9305E-08 | 6.00E-09 | 0.0003% | 18.1 | 0.0030% | 15.0 |
| 2.0E-07 | 2.0017E-07 | 5.62E-09 | 0.0001% | 20.2 | 0.0028% | 15.1 |
| 2.0E-06 | 2.0106E-06 | 3.63E-09 | 0.0053% | 14.2 | 0.0018% | 15.7 |
| 2.0E-05 | 2.0221E-05 | 5.00E-09 | 0.1106% | 9.8 | 0.0025% | 15.3 |
| 2.0E-04 | 2.0024E-04 | 5.11E-09 | 0.1189% | 9.7 | 0.0026% | 15.3 |

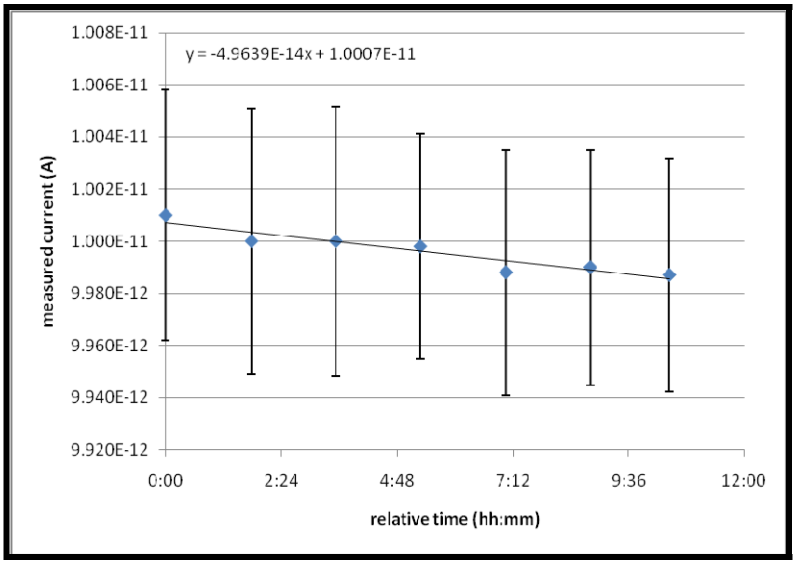


Fig. 7. Test 4 (10 hour stability test for 10 pA input)

## Field experience.

Field experience with the i404 has included the following issues:

- Nonzero (even negative) offset
- Nontriggered/polling artifact
- Saturation behavior

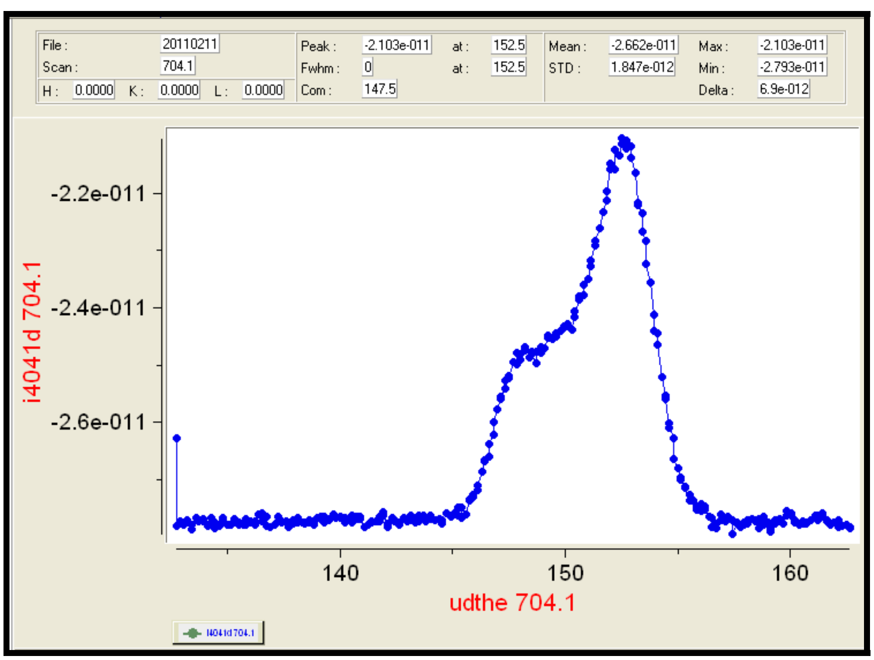


Fig. 8. Example scan data showing nonzero (negative) offset and polling artifact.

Nonzero offset can in principle be removed after the fact by applying an offset correction at the client side (EPICS). However, this takes extra setup and/or post-processing time. It would be preferable if zero correction can be applied in the autocalibration.

Bad points at the start of scans is seen from time to time and is thought to be an artifact of the polling. That is, when the current value is read from the i404 over RS232, the latest value is returned even if motors may have moved since then. To avoid this problem it is preferable to use some sort of triggering method to gather a new appropriately averaged current value upon readback request.

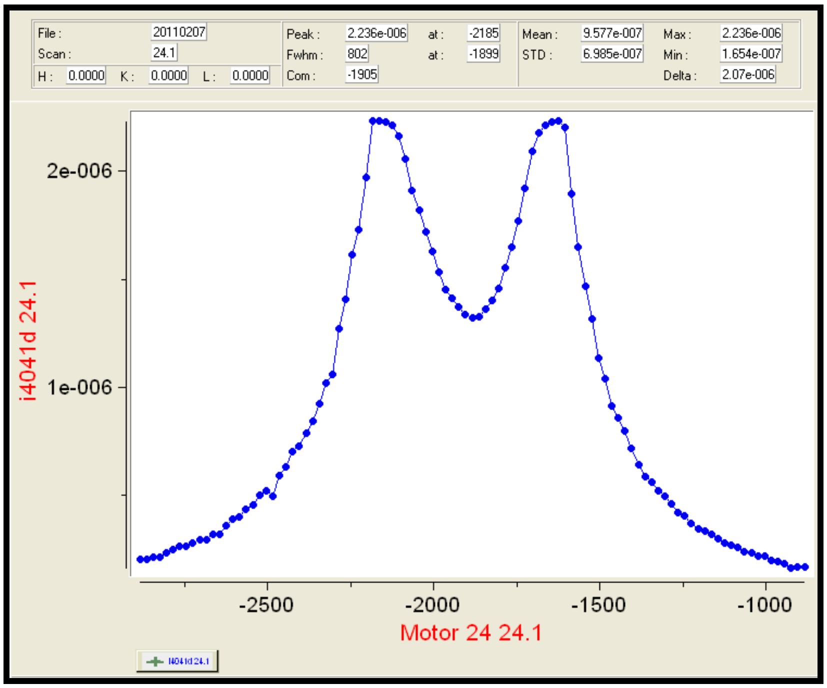


Fig. 9. Example scan data showing saturation behavior (single peak expected).

Avoiding saturation: use of the over-range bit could flag suspect data. However, this situation can be avoided altogether by either or both of the following:

Increasing the maximum current range (360 uA is not always enough).

Increasing the bit depth performance (true 16 or 20 bit values with 1 bit noise and accuracy), this allows use of higher ranges to accommodate lower currents (fewer range changes required). For low current measurements, digital rolling averaging can be applied to improve precision.

The signal read back under over-range conditions could be made flat (hold last known good value).

## Summary of Bugfixes and Features Requested.

- Readback text format: x.xxxxE-xx format needs updated, digital readback to only 5 decimal places is only 16 bits, should see 8 digit display
- Setting of 20 bits reverts to 16 when reading small range and doesn't go back at higher (should always use max)
- Mistake in user manual concerning monitor mode / frequency mapping selection values. (minimum value of conf:freq (to set absolute value) is 1, not 0 (0 is out of range despite what the manual says).
- Line termination and echoing issues should be resolved in communication protocol as identified above.
- Protected commands should be unprotected by default for ease of setup (e.g. line frequency selection). This is needed for operation in North American, Asia, and Europe.
- Ethernet (RJ45) cable interface preferred.
- **Multiple simultaneous ranges (independent ranges for each of the four channels). This would be extremely useful for generic data acquisition purposes.**
- Onboard digital **buffering**, rolling-**averaging** (configurable independently per channel) and waveform readback to extend range / resolution
- **Improved noise/speed performance (equivalent to 3-sigma noise of 10 fA @ 1 second or better)**
- **Improved accuracy to 50 fA / 20 bit on all scales**
- **Higher current ranges** (present limit appears to be 360 µA)
- Saturation / overrange performance could be improved (increasing maximum range, bit depth, and / or readback behavior)
- Improved internal calibration performance to remove dark current offset
- Onboard triggerable integration timer per each channel to give gated integration for pre-determined integration time (from 10’s of µs to 10’s of seconds) as needed for experiments with wide dynamic range requirements; digital accumulation (averaging) for 0.1, 0.2, 0.5 and 1.0 seconds would be commonly used and higher integration times could also be very useful. Presently the integration time is set by range selection; it would be valuable to allow selection by integration time (reading back range and preserving bit depth).
- Overall accuracy spec (including monitor outputs), guaranteed valid time period (calibration interval), and recalibration procedure as needed for standard / traceability. This is important for qualification of data used in beam diagnostics and scientific publication.