High Gain and Frequency Ultra-Stable Integrators for Long Pulse and/or High Current Applications

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Abstract:

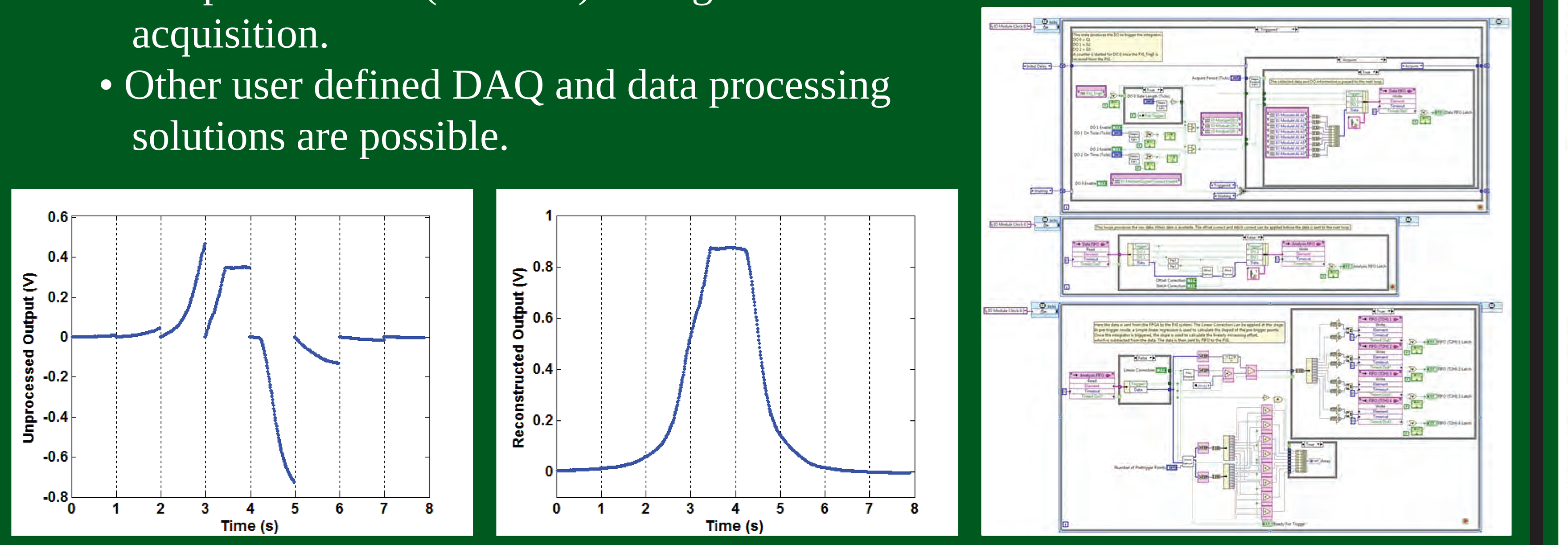
Inductive pickup loops are one of the primary magnetic diagnostics used in modern fusion and pulsed power concepts. To convert the direct voltage measurements from the inductive pickup loop to a measurement of magnetic field or current, the loop voltage must be integrated. Several factors make the integration difficult, especially for long-pulse applications requiring integrator stability for operational timescales from seconds to hours.

Eagle Harbor Technologies (EHT) has recently developed a new ultra-stable integrator that has a wide range of applications within the plasma science and pulsed power communities. It is the only integrator that meets (and dramatically exceeds) the ITER stability specification. With a sub 100 ns rise time, the integrator can integrate pulses ranging from 100 ns to 100 hours. Because of its extremely high gain and high frequency of operation, the integrator has an unprecedented effective dynamic range. For example, if given a 1 second square pulse input, using a 12 bit digitizer, the integrator can produce a post processed signal with 100 ns temporal resolution, and 22 bits of dynamic range information. This capability allows for extremely small high frequency detail to be resolved on much larger and slower signals.

The EHT Ultra-Stable integrator measures with high precision both extremely small fields, and extremely large fields. For example, if connected to a loop with a 0.1 m^2 area (100 turns 3 cm in diameter) wound on ferrite with a μ of 1000, the integrator would produce a 1 mV output when measuring a 100 pT field. When measuring medium to large fields, small air core pickup coils would be used. Since air core coils do not suffer saturation issues, the EHT integrator can measure very large currents, for very long times, without the usual droop and saturation issues encountered when using standard current monitors/transformers. There is no inherent limit to the maximum field size or current that can be measured. The new EHT integrator system, along with characterization data, will be presented.

Digital Zeroing and Data Reconstruction:

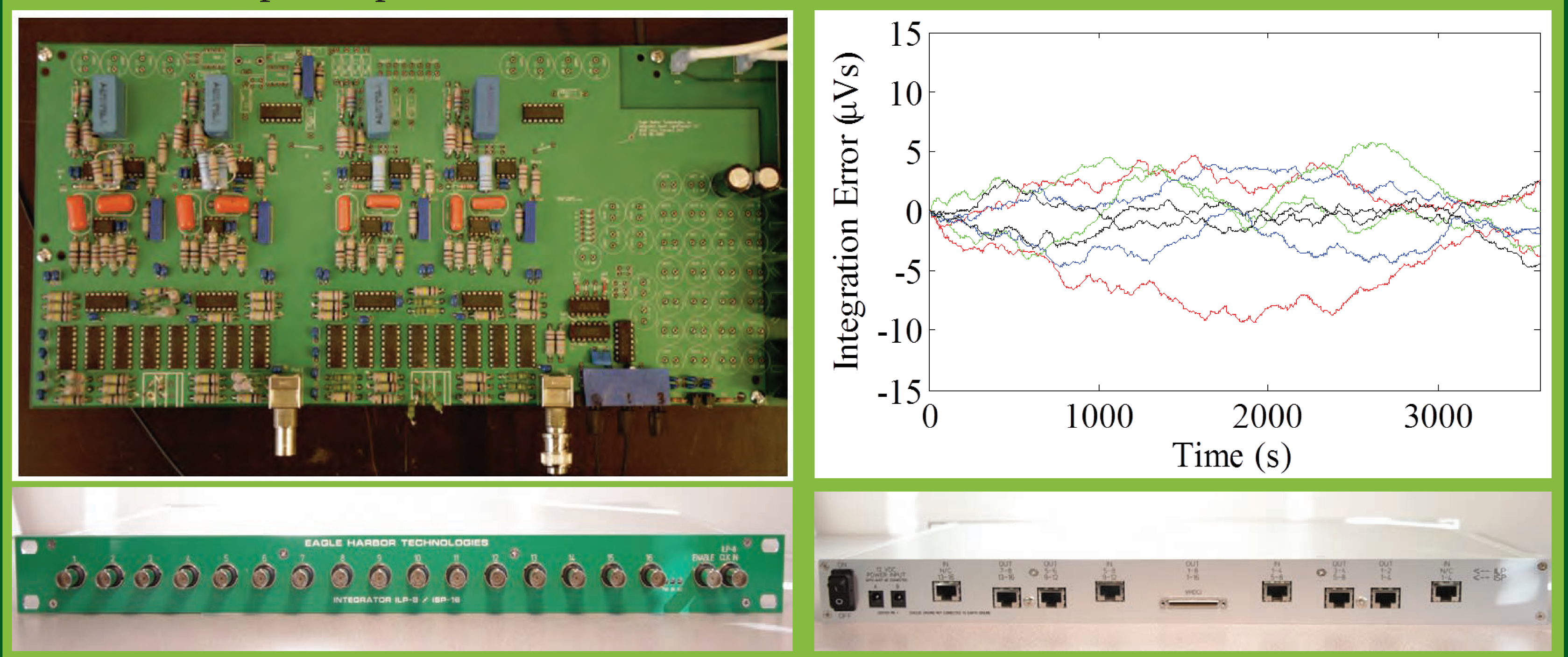
- Fast zeroing of integrator to maintain stability. Reset frequency is variable.
- Allows unprecedented dynamic range capability! Each segment can fill DAQ.
- Method employed for digital reset to achieve stability is patent pending.
- Data must be recombined to produce final profile.
- Post-processing is 2 to 3X more accurate than real-time processing due to use of post signal data.
- Real-time processing:
  - Pre-trigger samples to calculate offset and baseline corrections.
  - Currently uses National Instruments FPGA (NI PXIe-7962) for processing and Adapter Module (NI 5751) for signal acquisition.
  - Other user defined DAQ and data processing solutions are possible.



Left: Raw integrator output showing digital re-zeroing. Middle: Reconstructed signal. Right: FPGA code for data acquisition and real-time reconstruction writen in NI LabVIEW FPGA.

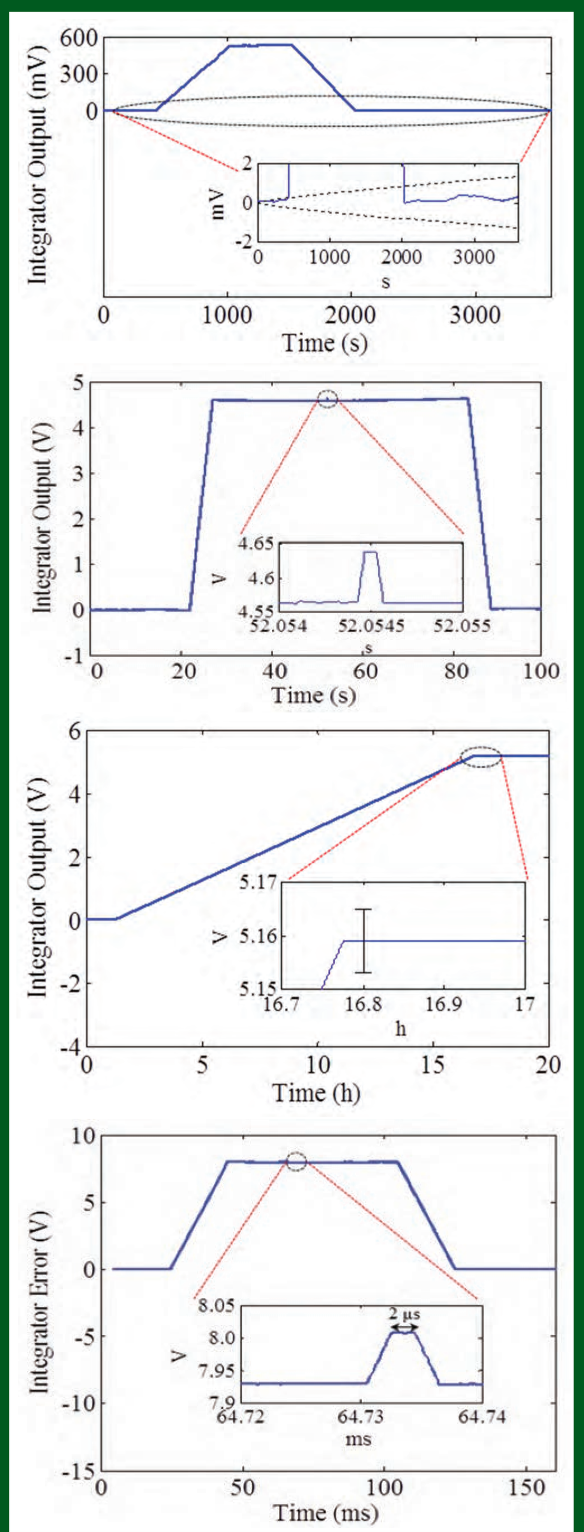
The EHT Hybrid Integrator:

- 5 MHz frequency response
- 1 μs to 100 ms RC time constant
- Drift Error: 5μV-s for 3600 s
- Extremely high dynamic range
- Fast, digitally controlled, reset process stabilizes analog integrator
- Auto zeroing feature eliminates trim pots
- 50 Ω to 100 kΩ factory settable impedance input
- Low output impedance



Top Left: Phase I prototype EHT Hybrid Integrator board. Top Right: Typical integration error for 3600 s shot lenght. Bottom: Phase II productized EHT Hybrid Integrator - front panel (left) and back panel (right) in 1U rack mountable box.

Integrator Testing:



A simulated slow magnetic field pulse was turned on from 500 – 1000 s and turned off from 1500 – 2000 s. After the pulse, the integrator remained gated on to collect drift data. The inlay shows the integrator's drift error is within ± 1 mV.

This example shows the frequency and resolution capabilities. A low-amplitude, fast signal is superimposed onto large-amplitude, slow magnetic fields. The integrator was operated with a 10 μs RC time and a 1 s reset interval. The inlay shows the expanded view of the fast pulse, where the integrated pulse characteristics are clearly resolved.

A 16 hour long signal was integrated. The integrator was operated with a 10 ms RC time and a 1 s reset interval. The error bars represent the uncertainty of the integration at this time and amounts to roughly 0.2% of the measured signal with an accumulated error of only ± 7 mV after 16 hours of integration.

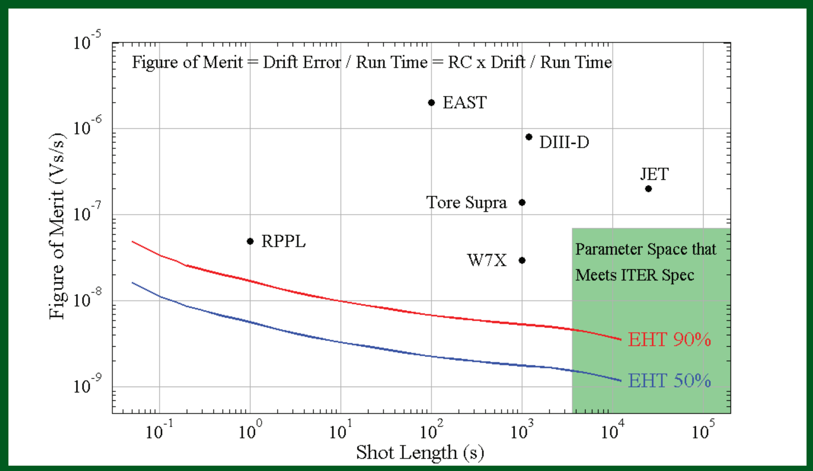
The EHT hybrid integrator can resolve fast and slow magnetic/plasma dynamics with the same integrator. A high-frequency pulse was superimposed onto a relatively slowly changing signal. The integrators were configured with a 100 ns RC \ constant and a 100 μs reset interval, which was fast compared with the experimental timescales of interest, typically 1 to 100 ms. The fast signal was clearly resolved.

ITER Application:

ITER Integrator Requirements:

- > 2000 channels.
- Pulse duration > 3000 s.
- Integration error < 250 μV-s/3600 s.
- HV fault mitigation. 500 V for 100 ms.
- Radiation induced common mode current rejection up to 1 μA.
- Up to 50 kHz frequency response.
- Robust to temperature variation.

Integrator Type	Test Conditions	Duration (s)	Drift (V)	RC (s)	Integration Error (V-s)	Fig of Merit (Vs/s)
ITER Target[9,11]	In Situ	>3600			$< 0.25\times10^{-3}$	$< 7\times10^{-8}$
Analog dig. comp. (JET)	Bench	25000		0.027	5×10^{-3}	2×10^{-7}
Volt to Freq conv. (JAERI)	Bench In Situ	200 2000			2×10^{-5} 1×10^{-2}	1×10^{-7} 5×10^{-6}
Hybrid dig/analog (DIII-D)	Bench In Situ	1200 1200	1×10^{-3} 5×10^{-3}	0.01 0.01	1×10^{-3} 5×10^{-3}	8×10^{-7} 4×10^{-6}
Dual comp. analog (Tore Supra)	In Situ	1000	5×10^{-3}	0.027	1.35×10^{-4}	1.4×10^{-7}
Wendelstein 7-X	In Situ	1000		0.001	3×10^{-6}	3×10^{-8}
KSTAR	In Situ	300	0.3	0.01	3×10^{-3}	1×10^{-5}
EAST	In Situ	100	0.01	0.02	2×10^{-4}	2×10^{-6}
RPPL analog integrators (TCSU)	Bench In Situ	1 1	5×10^{-3} 5×10^{-3}	1×10^{-5} 1×10^{-5}	5×10^{-8} 5×10^{-8}	5×10^{-8} 5×10^{-8}
EHT Phase I Prototype Integrators	Bench	1	6×10^{-7}	0.01	6×10^{-9}	6×10^{-9}
		10	3.5×10^{-6}	0.01	3.5×10^{-8}	3.5×10^{-9}
		100	2×10^{-5}	0.01	2×10^{-7}	2×10^{-9}
		3600	5.4×10^{-4}	0.01	5.4×10^{-6}	1.5×10^{-9}
		36000	3.6×10^{-3}	0.01	3.6×10^{-5}	1×10^{-9}
		1	6×10^{-4}	1×10^{-5}	6×10^{-9}	6×10^{-9}
		10	3.5×10^{-3}	1×10^{-5}	3.5×10^{-8}	3.5×10^{-9}
		100	2×10^{-2}	1×10^{-5}	2×10^{-7}	2×10^{-9}
		3600	5.4×10^{-1}	1×10^{-5}	5.4×10^{-6}	1.5×10^{-9}
		36000	3.6	1×10^{-5}	3.6×10^{-5}	1×10^{-9}
		100	4	1×10^{-7}	4×10^{-7}	4×10^{-9}



Above: Table showing comparison of EHT Integrator with other long pulse integrators and ITER specification. Left: Graph of integrator figure of merit as a function of integrator shot length for different long pulse integrators.

Current Monitor Application:

- 40 kA, 100 kHz PWM power supply for precision magnet waveform control.
- Due to high current and pulse duration, measurement with a current transfomer is not possible.
- Rogowski coil and integrator used to measure current for power supply testing.
- Extremely compact system for droop free current measurement.

Purple: Current, measured by droop-free integrator
Green: Current measured by current transfomer

Long Pulse Integrator Phase II Program:

- Produce 2nd generation multiple channel integrator system. (Two Versions)
  - Long Pulse Integrator (> 1 s Operation) for tokamaks
  - Short Pulse Integrator (< 1 s Operation) for small-scale DOE supported discovery experiments
- Design and test system for additional ITER specifications:
  - High input impedance, > 10 kΩ
  - Transient high voltage immunity
  - Radiation induced common mode current rejection
  - Thermal response
- Add Real-Time Data Acquisition and Control Options for Long Pulse System.
- Test 2nd generation systems at relevant experimental facility.
  - Long Pulse testing will be accomplished utilizing a DIII-D subcontract
  - Short Pulse testing will be conducted at the HIT-SI facility at the University of Washington
- Develop commercial versions of both systems

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