High Gain and Frequency Ultra-Stable Integrators for ICC and Long Pulse ITER Applications

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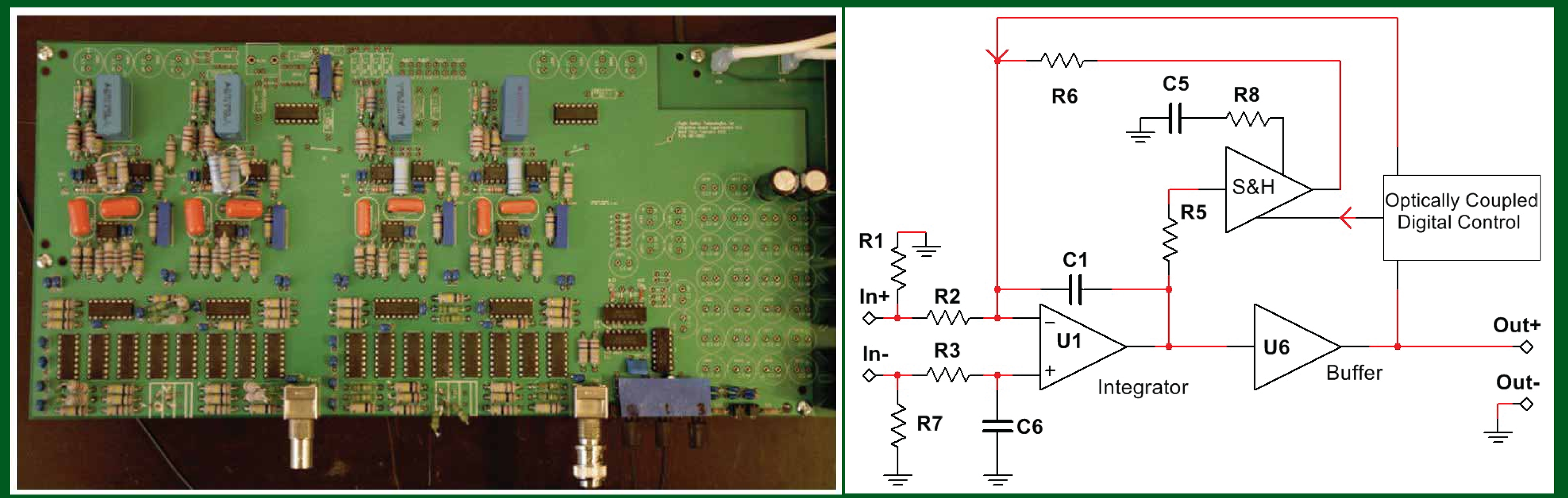
Abstract:

Eagle Harbor Technologies has developed a high gain and frequency ultra-stable integrator for small scale concept experiments and long pulse ITER applications. The Phase I integrator has a 10 µs RC time with a frequency response greater than 10 MHz. The device has been operated for the 3600 s with a drift error less than 600 µV, which exceeds the ITER specification. Longer period operation is also possible (> 30 hours). Additionally, this integrator has an extremely large dynamic range thereby increasing the effective bit depth of a digitizer. These integrators allow for both the fast and slow magnetic/plasma dynamics to be resolved with a single diagnostic. Data will be presented demonstrating the success of the Phase I program, and the Phase II work plan will be discussed. Work has begun to incorporate the integrators into legacy (CAMAC) and modern (National Instruments) DAQ systems.

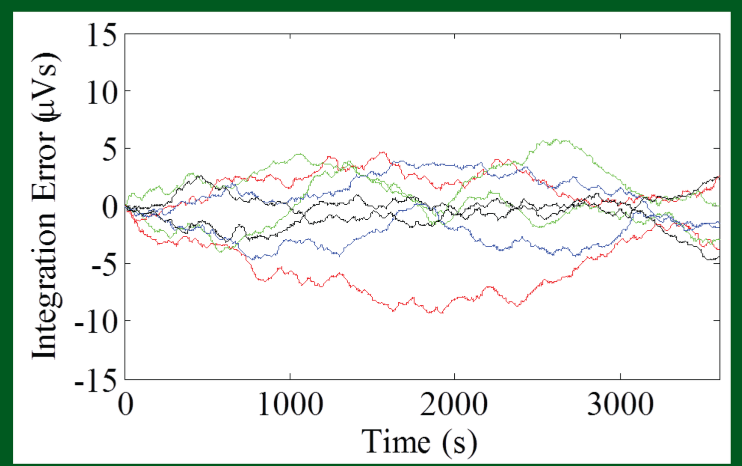
EHT Hybrid Integrator:

EHT has developed an analog/digital hybrid integrator that adds a fast digitally controlled reset and re-zero process to an analog integrator circuit that re-stabilizes the integrator. The integrator and the sample and hold circuit reset process is very fast (~100 ns). During this time, data is not recorded, which effectively limits the bandwidth. However, signal measurements with a resolution of 5 MHz or greater is possible, which is sufficient for most fusion applications including the small scale concept exploration experiments. The reset interval ranged from 100 µs to 10 s. The Phase I prototype for a two channel hybrid integrator and basic circuit diagram are shown below.



The EHT hybrid integrator (Left) and circuit diagram (Right).

Integration error for timescales relevant to ITER (3600 s) has been measured (Right). The time between integrator resets was 1 s, and the RC value was 10 ms. Here the system produced an average integration error of ± 5 µV-s for one hour of operation. This result compares very favorably to the values reported for the Tore Supra integrator of ± 5 mV-s for the same operation duration and is well under the ITER specification.



Typical integration error for several runs of three hour duration.

Key Advantages of the EHT Hybrid Integrator:

1. The EHT Hybrid Integrator design allows for high temporal resolution of both fast (megahertz) and slow (millihertz) signals at the same time, with the same integrator.

2. Random error/noise, which is always present, can be reduced to approach its theoretical limits by decreasing time between resets .

3. The dynamic range of the integrator is significantly increased and can be selected to match the application and available digitizers by varying the reset interval.

4. Signals can be scaled to fill the integrator's output/digitizer's input by simply adjusting the reset interval by varying the reset interval.

Comparison with other Integrators:

Integrator error data was collected over a wide range of pulse lengths and RC values (Table). The EHT integrator exceeds the ITER duration and integration error specification using RC values of 10 µs and 10 ms by a factor of ~20.

$$\textit{figure of merit} = \frac{\delta V_{drift} RC}{T}$$

The figure of merit does not degrade as the integrator's gain (RC time constant) is varied. This is significant since it allows for the integrator's gain to be set independently of the integrator's figure of merit. An integrator with a 100 ns RC time constant will work just as well for a given total integration time as one with a 10 ms RC time constant.

A consequence of the hybrid nature of the EHT integrators is that the figure of merit improves (decreases) with run time, which differs from most other integrator systems, where the figure of merit performance degrades (grows) with duration.

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}

EHT hybrid integrator performance compared to existing long-pulse integrators.

The figure of merit was measured as a function of integration time (Right). Two values of confidence level are show for the EHT integrator. The 50% value represents the average figure of merit deduced over multiple measurements. The 90% confidence level represents the figure of merit that 9 out of 10 measurements would fall below and still significantly exceeds the ITER specifications. The figure of merit decreases in time, but the integration error is not purely random. In practice, it would be nearly impossible to build a perfect integrator, so this result is expected.

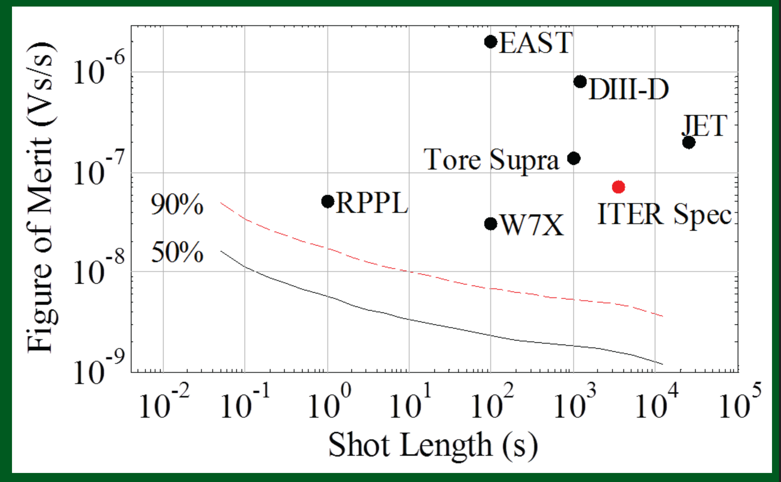
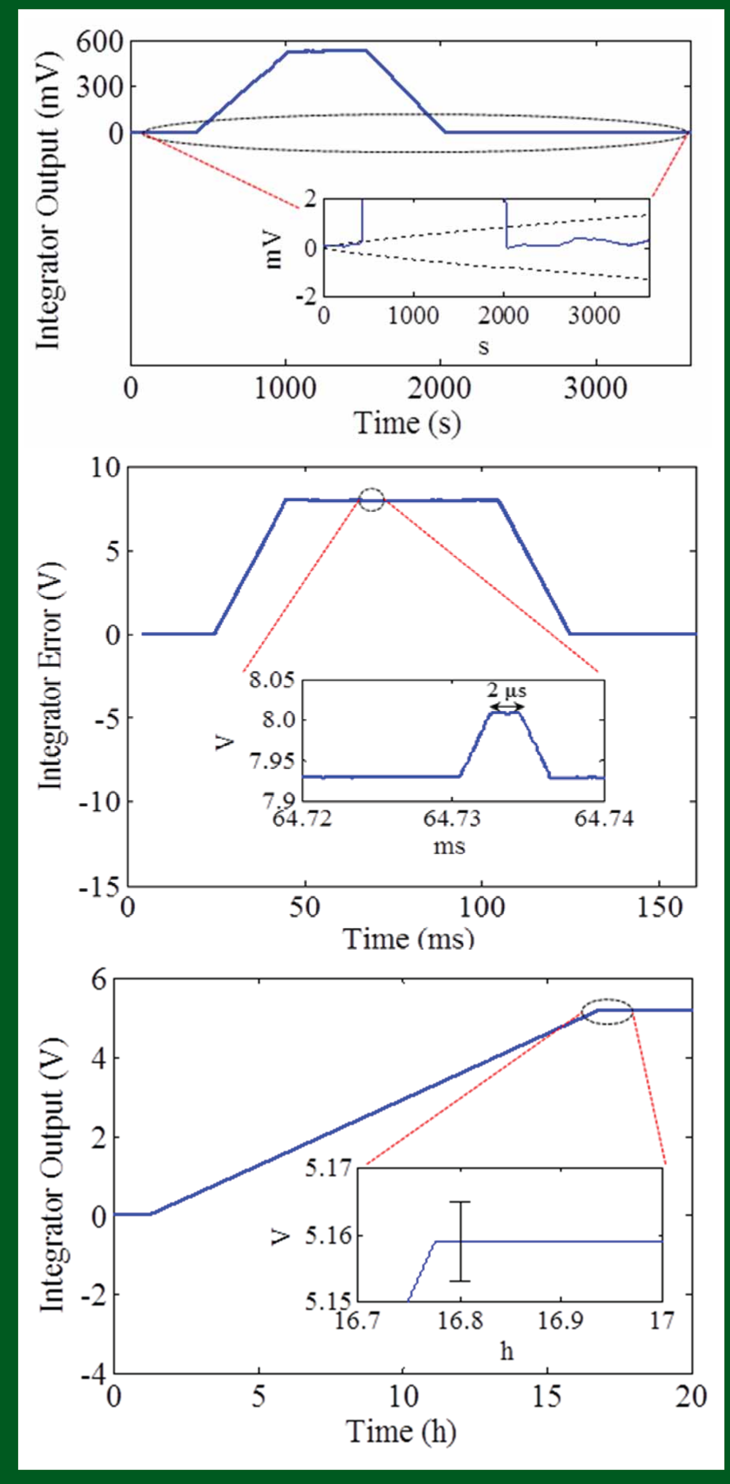


Figure of merit vs. integration time for the EHT Hybrid Integrator.

Long Duration Integrator Testing with Simluated Input Signals:



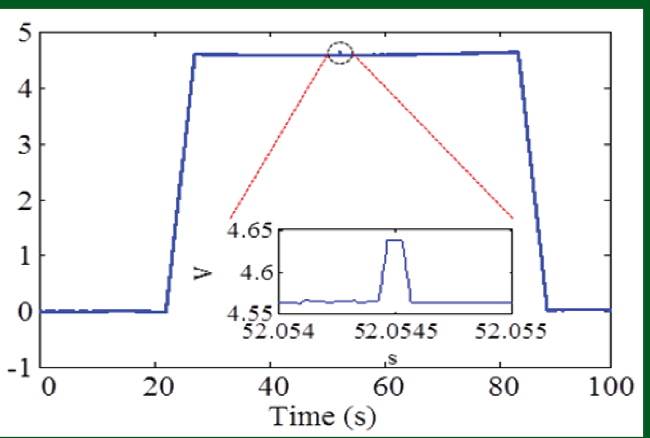
A simulated slow magnetic field pulse was turned on from 500 – 1000 s and turned off from 1500 – 2000 s. After the simulated magnetic pulse, the integrator remained gated on to collect drift data. The inlay shows the integrator's drift error is within ± 1 mV.

This example shows the frequency and resolution capabilities by simulating experiments where low-amplitude, fast signals are 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.

The long-duration stability of the integrator was demonstrated by integrating a 16 hour long signal. 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.

Testing for Small-Scale Concept Exploration Experiments:

These experiments require high temporal resolution and dynamic range for measurements of very fast plasma dynamics. The EHT hybrid integrator was tested to determine its performance for the small scale exploratory experiments. The integrators were reconfigured with a 100 ns RC time constant and a 100 µs reset interval, which was fast compared with the experimental timescales of interest, typically 1 to 100 ms. This allowed resolution of fast and slow magnetic/plasma dynamics with the same integrator. In the figure, a high-frequency pulse was superimposed onto a relatively slowly changing signal. The inlay shows that the fast signal was clearly resolved.



Phase II Program Objectives:

1. Produce Phase II integrator prototype including real-time data processing.

2. Validate prototype performance for small-scale concept exploration experiments (< 1 s) and ITER and burning plasma (> 1 s) timescales.

3. Incorporate integrator design with standard data acquisition and control system hardware (PXIe and CAMAC).

4. Produce demonstration integrators and field test in relevant experimental conditions for both short (HIT-SI) and long-pulse applications (DIII-D).

5. Collaborate with ITER and demonstrate integrator performance meets specifications including long-pulse operation (> 3600 s).

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